

PRACTICAL ELECTRICAL ENGINEERING

DIRECT CURRENTS

A MANUAL FOR USE IN INDUSTRIAL AND EVENING
SCHOOLS AND FOR HOME STUDY

BY
HARRY G. CISIN, M. E.
ENGINEERING EDITOR, "ELECTRICAL RECORD"

68 ILLUSTRATIONS



NEW YORK
D. VAN NOSTRAND COMPANY
EIGHT WARREN STREET
1922

FNGU.

TK

146

.CEY

COPYRIGHT, 1922
BY D. VAN NOSTRAND COMPANY

Printed in the United States of America

**In Memory
OF
MY MOTHER**

399071

PREFACE

THIS book was written for the use of Industrial and Evening schools and also as a home-study text. The basic principles of direct-current electrical engineering are presented, the keynote being simplicity. The only requisite for a full comprehension of the text is a knowledge of simple arithmetic, for mathematical derivations and proofs are dispensed with. This book is the only one, within the author's knowledge, on this phase of electrical engineering which does not use symbols and does not require a knowledge of algebra.

The course gives a correct and definite conception of the principles forming the foundations of electrical engineering. It is laid out according to a specific and logical plan. First, the fundamental units of the "practical" system are defined and explained. It is necessary for the student to learn and memorize these units as they will be used continually and will serve as his tools. It is then necessary to become acquainted with the fundamental laws of electrical engineering. Having mastered these, the student is ready to attack the more difficult problems which arise. After the fundamental laws, the properties of electrical and magnetic circuits are discussed. Under this heading (lesson 3) the author has endeavored to present the subject of "Current-Carrying Capacity" in a thorough and novel manner. When this much of the text has been mastered, the student has a sure groundwork. Electrical instruments are next taken up. Instead

of going into constructional details, the basic principle governing the operation of each type of instrument is shown. The next lessons are devoted to direct-current measurements and to primary and secondary cells, and these are followed by lessons on direct-current generators and motors. Fundamental laws are always referred to, so that the student increases his knowledge step-by-step and in a logical manner. The appendix contains a complete laboratory course of twenty experiments which will be found serviceable in supplementing the text.

The topical form of the text and the use of main headings and sub-headings serve to emphasize the important points of the subject. The outlines preceding each lesson will prove of value to the instructor in preparing his lectures, and to the student in summarizing and in reviewing his text assignments.

The electrician who has gained his knowledge of things electrical by actual practice can obtain from this book a real understanding of the basic principles of electrical engineering. Having mastered the text, he will know "why" as well as "how." There are a number of men engaged in the electrical industry, many in important executive and non-technical positions, who have had neither the time nor the opportunity to obtain even a general knowledge of electrical science. Such men will find in this book exactly what they have been looking for — the facts presented in simplified but not childish form and in a manner which can be grasped by those who do not possess either a college education or technical training.

H. G. CISEN

JANUARY, 1922

CONTENTS

LESSON 1	PAGE
ELECTRICITY AND MAGNETISM	3
LESSON 2	
FUNDAMENTAL LAWS OF ELECTRICAL ENGINEERING	14
LESSON 3	
ELECTRICAL AND MAGNETIC CIRCUITS	36
LESSON 4	
ELECTRICAL INSTRUMENTS	87
LESSON 5	
DIRECT-CURRENT MEASUREMENTS	115
LESSON 6	
PRIMARY AND SECONDARY (STORAGE) CELLS	141
LESSON 7	
THE ELECTRICAL GENERATOR	167
LESSON 8	
THE DIRECT-CURRENT MOTOR	232
APPENDIX	
LABORATORY EXPERIMENTS	275

Outline of Lesson 1 — ELECTRICITY AND MAGNETISM

1. ELECTRICITY:

(a) What Electricity is.

(b) How Manifested:

- (1) Magnetic effect.**
- (2) Heating effect.**
- (3) Chemical effect.**
- (4) Physiological effect.**
- (5) Visible effect.**

(c) How Measured:

- (1) Magnetic effect.**
- (2) Heating effect.**
- (3) Chemical effect.**

(d) Elementary Electrical Terms:

- (1) Current.**
- (2) Electromotive force (e.m.f.).**
- (3) Potential.**
- (4) Resistance.**
- (5) Conductance.**
- (6) Inductance.**
- (7) Difference between d.c. and a.c.**

(e) How obtained commercially:

- (1) Generator.**
- (2) Primary cell.**

(f) Electrical Units — Practical System:

- (1) Ampere.**
- (2) Ohm.**
- (3) Volt.**
- (4) Coulomb.**
- (5) Farad.**
- (6) Henry.**
- (7) Joule.**
- (8) Watt.**

2. MAGNETISM:

- (a) Definition.
- (b) How Measured.
- (c) Elementary Magnetic Terms:
 - (1) Magnetic Field.
 - (2) Lines of Force.
 - (3) Magnetic Flux.
 - (4) Magnetomotive force.
 - (5) Reluctance.
 - (6) Permeance.
 - (7) Polarity.
- (d) How Obtained:
 - (1) Electrically.
 - (2) Natural magnet.
 - (3) Permanent magnet.
- (e) Magnetic Units — Practical System:
 - (1) Ampere-turn.
 - (2) Maxwell.
 - (3) Rel.
 - (4) Other magnetic units.

PRACTICAL ELECTRICAL ENGINEERING

LESSON 1 — ELECTRICITY AND MAGNETISM

1. Electricity

(a) *What Electricity is.* Electricity, according to the modern conception, is the fundamental substance of which every form of matter is composed. The particles of electricity, or "Electrons," are the smallest conceivable sub-division of matter. Electricity in motion is a form of energy, just as heat is a form of energy. Light is the only visible form of energy. Electricity in motion, as well as all other forms of energy, must be observed and measured by the effects produced. Thus, heat energy may cause the temperature of a body to rise, and this rise in temperature is a manifestation of the presence of the heat energy, and if properly observed, may serve as a measure of it. (NOTE: The term "Electricity" as used hereafter, will refer to electricity in motion.)

(b) *How Manifested:*

(1) *Magnetic effect.* Electricity is always accompanied by magnetism, and can always be observed by means of it.

(2) *Heating effect.* Electrical Energy is always partially converted into heat energy.

(3) *Chemical effect.* Electricity produces certain chemical effects, chief among which are:

Plating of metals.

Electrolysis: This is the breaking up of a substance into its various elements by means of the passage of electricity through it.

(4) *Physiological effect.* The presence of electricity may be detected by the sense of touch.

(5) *Visible effect.* Electrical Energy may manifest itself as a discharge, such as lightning; or in certain cases it may cause a hazy light known as "Corona"; or it may cause lights in the sky, known as "Northern" and "Southern" lights.

(c) *How Measured:*

(1) *Magnetic effect.* This furnishes the most important means of measuring electricity.

(2) *Heating effect.* A secondary means of measuring electricity.

(3) *Chemical effect.* Mainly used for determining standards, and for purposes of calibration.

(d) *Elementary Electrical Terms:*

(1) *Current.* The movement or "flow" of electricity along a conductor is called an electric current. Current is measured in amperes.

(2) *Electromotive force (e.m.f.).* This is electrical pressure. It is the cause of current flow. The flow of electricity along a conductor may be likened to the flow of water through a pipe. The e.m.f. is analogous to the head or water pressure and the electric current to the rate of discharge of the water. E.m.f. is measured in volts and is also referred to as Voltage.

(3) *Potential* is electrical "level." It refers to the degree of e.m.f. A water analogy will make this clearer. The height or head of water is often measured from an arbitrary base such as sea level. In like manner, the degree of e.m.f., or the electrical level, or in other words the "Potential," is measured from an arbitrary base. This base is the earth, which is said to have zero electrical potential. "Difference of Potential" means a difference of electrical level, and is measured in volts. Although the term electromotive force correctly denotes electrical pressure, it should not be used to take the place of "difference of potential," when reference is being made to degree of e.m.f. or difference of electrical level.

(4) *Resistance*. Every conductor of electricity offers a certain resistance to the flow of current. Resistance is a property of the conductor itself. It increases with increased length of conductor, decreases with increased cross-sectional area, and varies with different materials. Resistance is measured in Ohms.

(5) *Conductance*. This term expresses the ease of flow of electric current. It is the reciprocal of resistance and equal to the resistance divided into the number one.

(6) *Inductance*. Inductance is the property of an electrical circuit which determines the value of the induced e.m.f. in that circuit, when current is changed at a definite rate. Inductance will vary with the shape of the conductor, and also with various other physical properties. It also varies according to the nature of the associated magnetic circuit. (Thus, iron or steel in the vicinity of the conductor will increase the inductance.) Inductance is measured in henrys.

6 PRACTICAL ELECTRICAL ENGINEERING

(7) *Difference between d.c. (direct current) and a.c. (alternating current).* "Direct current is current which flows in one direction. If it varies regularly in magnitude, it is said to be "pulsating," while if it remains the same in magnitude it is called "continuous." The term d.c. or direct current, when not otherwise qualified, refers to a continuous, non-pulsating direct current. An alternating current (a.c.) is one which regularly reverses its direction. It is a current which gradually increases from zero to a maximum value, and then decreases at the same rate to zero. It then reverses in direction, increasing from zero to a maximum value and returning back to zero again. These reversals take place at a very rapid rate.

(e) *How obtained commercially:*

(1) *Generator.* This machine furnishes the commercial means of obtaining electrical energy from mechanical energy.

(2) *Primary cell.* This is a secondary means of obtaining electricity. Its properties are based on electro-chemical action.

(f) *Electrical Units—Practical System.* A thorough knowledge of this simple system will serve all the purposes to which the older and more complicated systems have been applied. Although the Practical system is based originally

(NOTE: There are two other systems of units. In the "Electromagnetic System," the units are based on the force exerted between a current and a magnetic pole. Electrical and magnetic units are derived on this basis, using the fundamental units of length, mass, and time the centimeter, the gram, and the second (C. G. S. system). In the "Electrostatic System," the units are based on the force exerted between two quantities of electricity. The derived units are in terms of the C. G. S. system also. Since the units of both these systems are neither convenient nor necessary for the understanding of the theory of Electrical Engineering, they will not be discussed in detail.)

on the C.G.S. systems (see note below), still it is in no way dependent upon them for practical use. Hence it is entirely reasonable to consider the ampere, the volt, and the ohm, as fundamental units, from which all other electrical as well as magnetic units, when used together with the fundamental units of length and time, can be derived. Although the fundamental unit of length in the United States, is the meter, the English system is generally used in this country for measurements of length, and hence, in this book, the foot will be considered arbitrarily, as the fundamental unit of length. The second is the fundamental unit of time. The ampere and the ohm have been specifically defined by international agreement, the volt being determined as the product of these two.

The following are the fundamental and derived electrical units of the practical system:

(1) *Ampere*. This is the unit of electric current flow, and is specified as the unvarying current, which when passed through a solution of silver nitrate in water, and in accordance with standard specifications, will deposit silver at the rate of 0.000039 ounce (approximately two millionths of a pound) per second.

(2) *Ohm*. This is the unit of electrical resistance. Resistance is a property of all electrical circuits. The Ohm is specified as the resistance offered to an unvarying electric current by a column of mercury, at the temperature of melting ice (32 degrees Fahrenheit), 0.5050 ounce in mass (approximately $\frac{3}{1000}$ ths of a pound), of a constant cross-sectional area, and of a length of 3.487 feet.

(3) *Volt*. The volt is the unit of electrical pressure, or of electromotive force. It is that e.m.f. which, when

steadily applied to a conductor whose resistance is **one** ohm, will produce a current of one ampere. It may **also** be defined as the equivalent of $\frac{10,000}{10,183}$ times the e.m.f. of a Weston Normal Cell, at 68 degrees Fahrenheit.

(4) *Coulomb*. This is the unit quantity of electricity, being the amount of electricity flowing through a circuit in one second when the current flow is constant and equal to one ampere.

(5) *Farad*. This is the unit of capacity. Capacity is another property of electrical conductors. The farad is the capacity of a conductor, or system of conductors, which will be charged to a potential of one volt, by one coulomb of electricity. Since the farad is too large a unit for ordinary measurements of capacity, the "microfarad" is generally used. This is equal to one-millionth of a farad.

(6) *Henry*. This is the unit of inductance. The henry is the inductance of a circuit, when a current changing at the rate of one ampere per second induces an e.m.f. of one volt. The milli-henry, which is equal to one one-thousandth of a henry is generally used to measure inductance, as the henry is too large.

(7) *Joule*. This is the unit of energy and of work. It is the energy expended, or the work done, in one second, when a constant current of one ampere flows through a constant resistance of one ohm. Since the joule is rather small for ordinary work, the "Kilowatt-hour" is more commonly used. This is equal to one thousand volt-ampere-hours.

(8) *Watt*. The watt is the unit of power. It is the power

developed when work is done, or energy expended, at the rate of one joule per second. The kilowatt is equal to 1000 watts and is used in measuring larger amounts of power.

2. Magnetism

(a) *Definition.* Magnetism is a manifestation of electricity which is characterized by the attraction or repulsion of soft iron or of conductors carrying electricity.

(b) *How measured.* Since magnetism and electricity are so closely interlinked, either one may be used to indicate the presence of the other. An electric current will flow if a closed conductor cuts across a magnetic field (see next paragraph) and the amount of this current, as measured by a suitably calibrated instrument, will then show the amount of magnetism.

(c) *Elementary Magnetic Terms:*

(1) *Magnetic Field.* Wherever magnetism is present, the space in the immediate vicinity is called a magnetic field.

(2) *Lines of Force.* These are theoretical lines, which map out the magnetic field, and which show the direction along which the magnetism acts. Lines of force are conceived as forming closed loops and the path they traverse is called the "magnetic circuit." The positive direction of the lines of force is arbitrarily taken as that in which the north-seeking end of a compass moves.

(3) *Magnetic Flux.* This may be considered as the total magnetism present at any cross-section perpendicular to the lines of force. Magnetic flux is analogous to current flow. That is to say, it is convenient to consider a flow of magnetism in the same way as we consider electricity to flow.

(4) *Magnetomotive force.* This is the force causing magnetic flow. Magnetomotive force, or m.m.f., is the magnetic cause, while flux is the magnetic effect, just as in electrical terms, electromotive force is the cause and current is the effect. M.m.f. is measured in ampere-turns.

(5) *Reluctance.* This is magnetic resistance. Just as all conductors of electricity offer electrical resistance to the flow of current, so all magnetic circuits offer "reluctance" to the flux.

(6) *Permeance.* This represents the ease of magnetic flow. It is analogous to conductance in electrical conductors. It is equal to the reciprocal of the reluctance.

(7) *Polarity.* A substance showing the characteristics of magnetism is said to be a "magnet." Lines of force flow out of one end of the magnet and into the other end. These ends, where the magnetic effect appears to be concentrated, are called "poles." The lines of force are considered to flow from the "north" pole, which is the end of the magnet corresponding to the north-seeking end of a compass. The other end of the magnet is called the "south" pole.

(d) *How obtained:*

(1) *Electrically.* This is the important commercial method of obtaining magnetism. The magnetism due to the flow of an electric current is termed "Electromagnetism." The magnetic field thus produced lies at right angles to the electric current flow.

(2) *Natural magnet.* The lode-stone (leading stone) is an iron ore which shows magnetic properties. This magnetism is attributed to the motion of the electrons within the iron.

(3) *Permanent magnet.* Hardened steel, which has been permanently magnetized, either electrically, or by stroking with another magnet, has several important commercial applications.

(e) *Magnetic Units — Practical System:*

(1) *Ampere-turn.* The ampere-turn is the unit of magnetomotive force. As mentioned above, magnetomotive force is the exciting cause of flux. An ampere-turn consists of a current of one ampere flowing through one complete turn of a conductor. The expression "turn" means that the conductor is wound in a solenoid. (That is, is wrapped around a core, which may consist of air or of any other substance.) The same magnetic field will result from ten ampere-turns consisting of ten amperes flowing through one turn, as from ten ampere-turns consisting of one ampere flowing through ten turns.

(2) *Maxwell.* The maxwell is the unit of magnetic flux. It is equal to one line of force. When 100,000,000 lines of force are cut by a single conductor, in one second, one volt will be induced. This then defines the maxwell in terms of the electrical effect.

(3) *Rel.* The name "Rel" has been suggested,¹ and is now widely used as the unit of reluctance. The rel is the reluctance of a magnetic circuit which will have one line of force in it, upon application of one ampere-turn. It can also be specified as the reluctance of a cylinder of air, or of any other non-magnetic material, one square inch in cross-sectional area, and 3.19 inches long.

(4) *Other magnetic units* such as "flux density," "field intensity," etc., have no generally adopted names. These will be explained in detail in the lesson on the magnetic circuit.

¹ Karepetoff

Outline of Lesson 2—FUNDAMENTAL LAWS OF ELECTRICAL ENGINEERING

1. ELECTRICAL LAWS:

(a) Ohm's Law:

- (1) Statement of Ohm's Law.**
- (2) Mechanical analogy.**
- (3) Ohm's Law stated as an Equation.**
- (4) Numerical examples.**
- (5) Ohm's Law applied to a portion of a circuit.**

(b) Laws of Electrical Power:

- (1) Definition of Power.**
- (2) Definition of Electrical Power.**
- (3) Electrical Power stated as an Equation.**
- (4) Numerical example.**
- (5) Equations for Electrical Power in terms of Resistance.**
- (6) Numerical examples.**
- (7) Definitions of Mechanical Power and Work.**
- (8) Relation between Mechanical Power and Electrical Power.**
- (9) Numerical example.**

(c) Laws of Electrical Energy and Electrical Heating:

- (1) Definition of energy.**
- (2) Method of determining amount of electrical energy.**
- (3) Equations of electrical energy.**
- (4) Numerical examples.**
- (5) Heat energy.**
- (6) Electrical Heating.**
- (7) Numerical examples of electrical heating.**

(d) Kirchhoff's Laws:

- (1) How derived.**
- (2) Divided circuits.**
- (3) Statement of Kirchhoff's First Law.**
- (4) Statement of Kirchhoff's Second Law.**
- (5) Numerical illustration of First Law.**
- (6) Numerical illustration of Second Law.**
- (7) Application to more complex circuits.**

2. MAGNETIC LAWS:

- (a) Ohm's Law for the Magnetic Circuit:
 - (1) Statement of Magnetic law.
 - (2) Mechanical analogy.
 - (3) Magnetic law stated as an equation.
 - (4) Numerical examples.
- (b) Laws of magnetic circuit with iron or other ferro-magnetic substances:
 - (1) Reluctance a variable quantity.
 - (2) Low reluctance.
 - (3) Effects of Hysteresis.
 - (4) Magnetization curves.
 - (5) Discussion of curves.
 - (6) Numerical applications of magnetization curves.

3. ELECTROMAGNETIC LAWS:

- (a) Production of Magnetic Field by Electrical Current:
 - (1) Field about a straight Conductor.
 - (2) Field about a Helix.
- (b) Laws of Magnetic Action between Current-Carrying Conductors:
 - (1) Parallel currents in the same direction.
 - (2) Parallel currents in opposite directions.
 - (3) Currents at an angle.
- (c) Maxwell's Law of Motor Action.
- (d) Law of Generator Action or of "Electromagnetic Induction":
 - (1) Statement of law.
 - (2) Magnitude of induced e.m.f.
 - (3) Value of induced e.m.f. expressed as an equation.
 - (4) Numerical example.
 - (5) Direction of current flow.
- (e) Lenz's Law.

LESSON 2 — FUNDAMENTAL LAWS OF ELECTRICAL ENGINEERING

1. Electrical Laws

(a) *Ohm's Law:*

(1) *Statement of Ohm's Law.* "Current flowing in a conductor will increase directly with increase of voltage and will decrease directly with increase of resistance."

In other words, voltage is the cause, while current is the effect; and the effect is directly dependent upon the cause and inversely upon the opposition offered to the cause. Ohm's Law is *the* fundamental law of electrical engineering.

(2) *Mechanical analogy.* Suppose that by exerting a certain effort, a man is able to walk a certain distance, on a smooth city road. With double the effort, he can walk double the distance. Assume that on a rough country road, with the same effort, he can walk only half the distance or with double the effort, he can walk the same distance. Applying this reasoning to electricity, a certain voltage causes a certain current to flow. Double the voltage will cause double the current to flow, if the resistance is the same. If the resistance is doubled however, the same voltage will result in only half the current flow. With double voltage and double resistance, the same current will flow.

(3) *Ohm's Law stated as an Equation:*

$$\text{Current (in amps.)} = \frac{\text{Voltage (in volts)}}{\text{Resistance (in ohms)}} \quad \text{Equation (1)}$$

Voltage = Current $\times$ ResistanceEquation (2)

Resistance = $\frac{\text{Voltage}}{\text{Current}}$ Equation (3)

The above simple equations all mean the same thing, and serve to express, in various forms, the idea set forth above. The substitution of numerical values in the place of names will make the meaning even clearer. It will be seen that if any two values are known, the third can easily be determined from these equations.

(4) *Numerical examples.* To find the current which will flow through a resistance of 5 ohms when an e.m.f. of 100 volts is applied at the terminals:

From equation (1), Current = $100/5 = 20$ amperes.

Suppose it is desired to determine the voltage drop when a current of ten amperes flows through a resistance of 15 ohms:

From equation (2), this will equal $10 \times 15 = 150$ volts.

If it is desired to find the resistance of a circuit, and it is found that 19 volts will cause 1 ampere to flow, then from equation (3), the resistance = $19/1 = 19$ ohms.

(5) *Ohm's Law applied to a portion of circuit.* Ohm's Law applies to a portion of an electrical circuit, as well as to the entire circuit. Care must be taken when applying the law to only a part of the circuit, to consider only the resistance, current and voltage of that part. This statement will be explained in greater detail under "Electrical Circuits."

(b) *Laws of Electrical Power:*

(1) *Definition of Power.* "Power is the rate of doing work." Thus, one man may perform a certain piece of work in a day, while another one may do the same thing

in an hour. The second man has expended greater power.

(2) *Definition of Electrical Power.* "Electrical Power is the product of voltage times amperage."

(3) *Electrical Power stated as an Equation:*

$$\begin{aligned}\text{Electrical Power} &= \text{Voltage (in volts)} \times \text{Current (in amps.)} \\ &= \text{Watts} \dots \dots \dots \text{Equation (4)}\end{aligned}$$

(4) *Numerical example.* If an e.m.f. of 15 volts, when impressed on a circuit will cause 10 amperes to flow, the electrical power is $10 \times 15 = 150$ watts. To express this in kilowatts, divide by 1000 thus: $150/1000 = 0.15$ Kw.

(5) *Equations for Electrical Power in terms of Resistance.* Substituting the value of voltage obtained from equation (2) in equation (4), the following is obtained:

Electrical Power

$$\begin{aligned}&= \text{Current} \times \text{Resistance} \times \text{Current} = \text{Watts} \\ &= \text{Current}^2 \times \text{Resistance} \dots \dots \dots \text{Equation (5)}\end{aligned}$$

In like manner, by substituting the value for current obtained from equation (1), in equation (4), the following equation is obtained:

$$\text{Electrical Power} = \frac{\text{Voltage}^2}{\text{Resistance}} \dots \dots \dots \text{Equation (6)}$$

Equations (4), (5), and (6) give the same results, but in some cases it is easier to obtain values of current and of resistance, or of voltage and resistance, than of voltage and current.

(6) *Numerical examples.* In the example given above, an e.m.f. of 15 volts resulted in a current of 10 amperes. Hence, from Ohm's Law, the resistance of this circuit was 1.5 ohms.

Then from equation (5):

$$\text{Electrical Power} = 10^2 \times 1.5 = 100 \times 1.5 = 150 \text{ watts.}$$

Also, from equation (6),

$$\text{Electrical Power} = 15^2 / 1.5 = 225 / 1.5 = 150 \text{ watts.}$$

These examples demonstrate the equality of the above formulas.

(7) *Definitions of Mechanical Power and Work.* Mechanical power is measured in Horse Power. One horse power is equivalent to 33,000 foot-pounds per minute. Since power is the rate of doing work, the expression for power must contain a time element and a work element. Work is a measure of a force exerted through a distance. Hence the foot-pound measures work. The three units—of force, length, and time—may be combined in any way, but so long as they equal 33,000 foot-pounds per minute, they measure one horse power. Thus, if a force of 33,000 pounds is exerted through a distance of one foot, in one minute, a horse power has been expended. The same power would be required if a force of one pound was exerted over a distance of 33,000 feet in one minute, or if a force of 33,000 pounds was exerted over a distance of $\frac{1}{2}$ foot in 30 seconds.

(8) *Relation between Electrical Power and Mechanical Power.* The mechanical unit of power, the hp. (horse power) is much larger than the electrical unit of power, the watt. The following equation expresses the relation between the two units:

$$746 \text{ watts} = 1 \text{ Horse Power} \dots\dots\dots \text{Equation (7)}$$

Hence to change from mechanical to electrical units, it is necessary to multiply by 746.

(9) *Numerical example.* To change 10 hp. to watts: $10 \times 746 = 7460$ watts. Since a large value such as this is more conveniently expressed in kilowatts, this would equal $7460/1000 = 7.46$ kw.

(c) *Laws of Electrical Energy and Electrical Heating:*

(1) *Definition of energy.* "Energy is the ability to perform work." It is closely related to work, and is measured in the same units, but does not mean exactly the same thing. Electricity (in motion) is energy, since it can do work. The degree to which it possesses this ability is a measure of its energy. Energy can neither be created nor destroyed. However it can be converted into various forms, which make it available for the production of various kinds of work. When energy is available for the production of work, it is referred to as *potential* energy. Energy at work is *kinetic* energy. Kinetic energy is sometimes called the energy of motion.

(2) *Method of determining amount of electrical energy.* While electrical energy is being expended, the work done may be measured. This is the most common method of determining the amount of electrical energy. Thus, electrical *energy* is sold to the householder, but the amount expended is measured by the work performed. This will be taken up further under the heading of "Electrical Instruments." Electrical energy may be expended in the production of (that is to say, converted to the form of) various other forms of energy, such as mechanical energy, light, or heat. The conversion of electrical energy into every form of energy is invariably accompanied by the conversion of a part into heat energy.

(3) *Equations of electrical energy.*

Work Performed or Energy Expended

$$= \text{Voltage (in volts)} \times \text{Current (in amps.)} \\ \times \text{Time (in sec.)} = \text{Joules. . Equation (8)}$$

By taking the value for voltage from equation (2) and substituting in equation (8), the following expression is arrived at:

Work Performed or Energy Expended

$$= \text{Current}^2 \text{ (in amps.)} \times \text{Resistance (in ohms)} \\ \times \text{Time (in sec.)} = \text{Joules. . Equation (9)}$$

The Kilowatt-hour is used for larger amounts of energy. Since the joule is equivalent to a watt-second, the kilowatt-hour is equal to $1000 \times 60 \times 60$ joules = 3,600,000 joules (since the prefix "kilo" is 1000, and there are 60×60 seconds in an hour). Therefore to express equation (9) in kilowatt-hours:

Work Performed or Energy Expended

$$= \frac{\text{Current}^2 \times \text{Resistance} \times \text{Time (sec.)}}{3,600,000} = \text{Kw.-hrs.}$$

Equation (10)

(4) *Numerical examples:*

To find the energy expended if 20 amperes flows through a resistance of 30 ohms for an hour:

From equation (9)

$$20 \times 20 \times 30 \times 3600 = 43,200,000 \text{ Joules}$$

To change this to kilowatt-hours, according to equation (10):

$$\frac{20 \times 20 \times 30 \times 3600}{3,600,000} = 12 \text{ Kw.-hrs.}$$

(5) *Heat energy.* Heat energy is usually measured in B.T.U.'s. (British Thermal Units.) A B.T.U. is a

measure of the heat energy required to raise the temperature of a pound of water from 62 degrees to 63 degrees Fahrenheit. It has been determined experimentally that the B.T.U. is equal to 778 foot-pounds.

(6) *Electrical Heating*. Since electrical energy and heat energy are mutually convertible, the *joule* is sometimes called the *electrical unit of heat*. Since the joule is equal to a watt-second, and 746 watt-seconds equal 550 foot-pounds, then one foot-pound equals 1.356 joules. Therefore one B.T.U. = 778 foot-pounds = 1055 joules. Dividing equation (9) by 1055, we obtain

Work Performed or Energy Expended

$$= \frac{\text{Amperes}^2 \times \text{Ohms} \times \text{Seconds}}{1055} = \frac{\text{Joules}}{1055}$$

$$= \text{B.T.U.'s} \dots \dots \dots \text{Equation (11)}$$

In order to find the increase of temperature, in degrees Fahrenheit, of a conductor (neglecting radiation losses, etc.), it is simply necessary to divide equation (11) by the mass of the conductor in pounds, and by its specific heat, as obtained from a handbook table.

(7) *Numerical examples of electrical heating*. To determine the heat energy, in B.T.U.'s liberated when a current of 15 amps. flows through a resistance of 10 ohms for 30 minutes.

From equation (11):

$$\frac{15 \times 15 \times 10 \times 60 \times 30}{1055} = 3838.8 \text{ B.T.U.'s.}$$

To find the temperature rise, in the above example, and assuming the conductor to weigh 250 pounds, to be made of

copper, and to have a specific heat of 0.096 (approximately):

$$\begin{aligned}\text{Temp. Rise (neglecting losses)} &= \frac{3838.8}{250 \times .096} \\ &= 159.9 \text{ degrees Fahr.}\end{aligned}$$

(d) *Kirchhoff's Laws:*

(1) *How derived.* These laws depend on Ohm's Law. They constitute a further application of Ohm's Law to more complicated electrical circuits.

(2) *Divided circuits.* In addition to simple electrical circuits, conductors may be connected in various complicated networks, all of which come under the heading of "divided circuits." By means of Kirchhoff's Laws, the current in any part of a divided circuit may be found, if the resistances of the various parts, and the e.m.f.'s are given.

γ (3) *Statement of Kirchhoff's First Law.* "The sum of the currents flowing to a point, in any electrical circuit, is equal to the sum of the currents flowing away from that point."

γ (4) *Statement of Kirchhoff's Second Law.* "In any closed electrical circuit, the sum of the impressed electromotive forces will equal the sum of the voltage drops." This statement requires modification, in so far as "addition" of voltages is concerned. Voltages are added, provided they are in the same direction, but must be subtracted if in opposite directions.

(5) *Numerical illustration of first law.* In Fig. 1, the sum of the currents, 8 amperes and 4 amperes, flowing towards point *a*, is equal to the total current, 12 amperes, leaving point *a*.

(6) *Numerical illustration of second law.* Assume that the

resistances of the various parts of the circuit, Fig. 1, are as marked, and that the total internal resistance of the battery is 0.06 ohm. Then, according to the statement of the second law, if the impressed voltage = 7.12 volts:

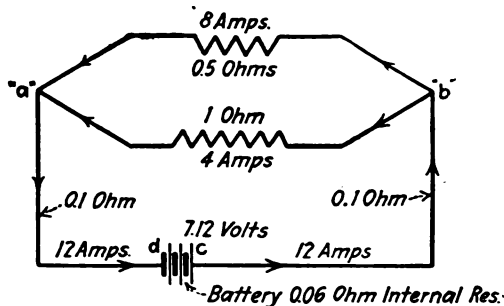


FIG. 1. — Diagram illustrating Kirchhoff's Laws.

Impressed Voltage = 7.12 = Total Voltage Drops through the lower circuit

$$\begin{aligned}
 &= 12 \times 0.1 \text{ (c to b)} \text{ plus } 4 \times 1 \text{ (b to a in lower branch)} \text{ plus } 12 \times 0.1 \\
 &\text{(a to d) plus } 12 \times 0.06 \text{ (d to c through battery)} \\
 &= \text{Total of 7.12 volts.}
 \end{aligned}$$

In like manner, Impressed Voltage = Total Voltage drop through upper circuit:

$$\begin{aligned}
 7.12 &= 12 \times 0.1 \text{ (c to b)} \text{ plus } 8 \times 0.5 \text{ (b to a through upper circuit)} \text{ plus } 12 \times 0.1 \text{ (a to d)} \text{ plus } 12 \times 0.06 \\
 &\text{(d to c through battery)} \\
 &= \text{Total of 7.12 volts.}
 \end{aligned}$$

(7) *Application to more complex circuits.* The above methods can be applied to more complex circuits. The precautions in regard to e.m.f. and voltage drop *direction* must be strictly observed. Numerical examples of more

complex circuits will be taken up in the next chapter under "Electrical Circuits."

2. Magnetic Laws

(a) *Ohm's Law for the Magnetic Circuit.* Under certain circumstances, a relationship exists in the magnetic circuit, which is of a similar nature to that existing in the electrical circuit. The magnetic phenomena is entirely different from the electrical one, but both are of that class in which the effect is proportional to the cause. This is the only reason for using Ohm's Law of the electrical circuit as an analogy.

(1) *Statement of Magnetic law.* "The total flux within a coil, having an *air core*, will increase directly with increase of applied magnetomotive force and will decrease directly with increase of reluctance of the magnetic circuit." This law will also hold good if the core is of any other substance, with the exception of iron, nickel, cobalt, manganese, chromium, magnetite, certain alloys of copper, manganese and aluminum, and some of the oxides of the metals named. These substances are called *ferro-magnetic*, since the laws governing their magnetic action are like those for iron. These will be taken up under a separate heading.

(2) *Mechanical analogy.* The analogy given for the electrical circuit, under Ohm's Law, applies equally well to the Ohm's Law of the magnetic circuit.

(3) *Magnetic law stated as an equation:*

Flux (in maxwells)

$$= \frac{\text{Magnetomotive force (in ampere-turns)}}{\text{Reluctance (in rels)}} \dots \text{Equation (12)}$$

Magnetomotive force = Flux $\times$ Reluctance. . Equation (13)

Reluctance = $\frac{\text{Magnetomotive force}}{\text{Flux}}$ Equation (14)

The above equations all have the same meaning and express the idea set forth above in a form convenient for the solution of actual problems.

(4) *Numerical examples.* To determine the flux which will be maintained in a magnetic circuit of 40 rels reluctance by a magnetomotive force (m.m.f.) of 20,000 ampere-turns:

From equation (12):

$$\text{Flux} = \frac{20,000}{40} = 500 \text{ maxwells (or lines).}$$

To determine the number of ampere-turns necessary to establish a flux of 2,000,000 lines of force (maxwells) through a reluctance of 0.004 rels:

From equation (13):

$$\text{M.m.f.} = 2,000,000 \times 0.004 = 8000 \text{ ampere-turns.}$$

To find the reluctance of a magnetic circuit consisting of 4000 turns, wound on an air core, if a current of 10 amperes will produce a flux of 2000 maxwells:

From equation (14):

$$\text{Reluctance} = 10 \times 4000 / 2000 = 20 \text{ rels.}$$

(b) *Laws of magnetic circuit with iron or other ferro-magnetic substance:*

(1) *Reluctance a variable quantity.* The reluctance of steel and iron is not constant, but increases with increase of flux density.

(2) *Low reluctance.* The reluctance of iron is very much less than that of non-magnetic substances.

(3) *Effects of Hysteresis.* If flux changes in iron or steel, there is a loss of energy due to magnetic friction within the substance. This is called "Hysteresis." Because of hysteresis, the same m.m.f. will not always produce the same flux in a piece of iron or steel. The flux will be lower if the excitation is increasing than if it is decreasing, since the material offers internal resistance to the change of magnetization.

(4) *Magnetization curves.* These are also called "saturation curves." They are used in the design of the magnetic circuits of electrical machinery. By means of these curves, it is possible to *picture* the laws governing the variation of flux in any ferro-magnetic material, as the exciting force is varied. The magnetic properties of these materials cannot be expressed by a simple equation such as given under the "Ohm's Law of the Magnetic Circuit" (for non-magnetic materials). Hence curves furnish a very convenient and simple means of showing these properties without the use of higher mathematics. The curves shown in Fig. 2 are obtained as the results of tests and these represent average values for the materials named. It should be noted that the values plotted in the horizontal direction (the abscissa) are for ampere-turns per inch length. This value is called *Magnetic Intensity* and is more convenient for purposes of calculation than "ampere-turns." The same thing applies to the values plotted in a vertical direction (ordinates). Here, the lines of force per square inch, or the *Flux Density* is used, instead of simply total flux. It can

readily be seen, that values taken from these curves can be applied to a magnetic circuit of any length and of any cross-sectional area.

(5) *Discussion of curves.* It can be seen from the curves of magnetization of the various materials, that cast iron

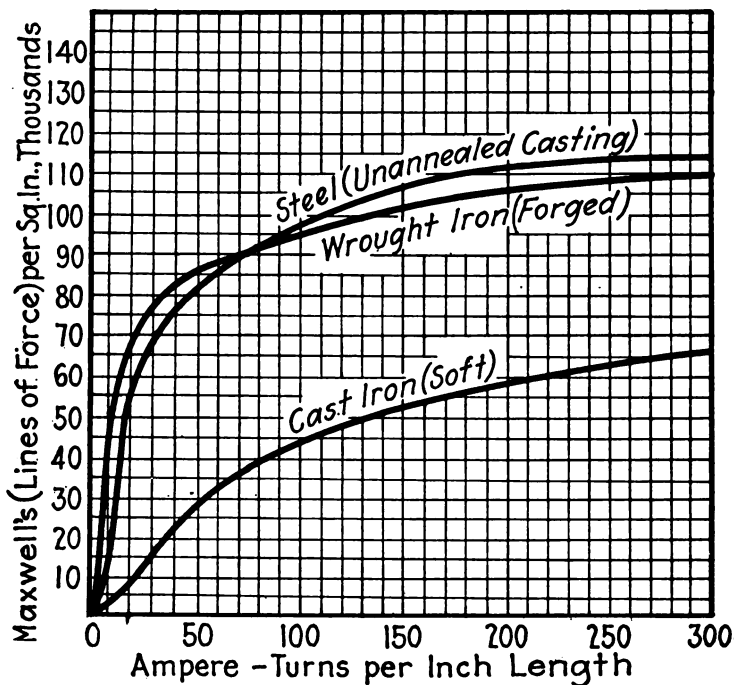


FIG. 2. — Magnetization curves.

shows the poorest magnetic properties. In other words, the same number of ampere-turns per inch, if applied to forged steel, would give an enormously increased number of lines of force per square inch than would be obtained with cast iron. The cast iron not only shows greater reluctance to the flux, but it will not stand as

great a flux density as the forged steel. The way in which these properties vary for the different materials, is apparent by simply glancing at the curves. A point is reached, in every magnetic material, where further increase of magnetic intensity will not produce any further increase of flux density. At this point, the material is said to be *saturated*. It can be seen that cast iron becomes saturated at a lower flux density than the other materials. The reason for its wide use lies in its lower cost, its ease of casting and of machining. Cast iron could not be used where a high flux density was required, as in a generator armature core, since it would reach its point of saturation too soon.

(6) *Numerical applications of magnetization curves.* These will be given in the next lesson under "Magnetic Circuits."

3. Electromagnetic Laws

(a) *Production of Magnetic Field by Electrical Current.* The flow of electricity will always be accompanied by the production of a magnetic field. The direction of this field will always bear a fixed relation to the current direction. The strength of the field will be directly proportional to the current strength.

(1) *Field about a Straight Conductor.* The relation between current flow and direction of magnetic field can be remembered by the aid of several rules. If a current-carrying conductor is grasped in the right hand, with the thumb pointing in the direction of current flow, the fingers will point in the direction of the magnetic flux. Another aid to remembering this relation is the motion of the corkscrew, which goes in as it is turned clockwise.

Similarly, if a current is flowing into a conductor, the lines of force are in a clockwise direction about it. The direction of the magnetic field around a current-carrying conductor can easily be verified by means of a small compass. Knowing the relationship existing between direction of current flow and magnetic field, the compass furnishes a simple means of determining direction of current flow. Thus, if a compass is placed under a current-carrying conductor, and the conductor is pointed in a north and south direction, and the needle deflects to the west, the flow of current is from south to north. (Remember the word "snow" — thus south to north, deflection west.)

(2) *Field about a Helix.* If a current-carrying conductor is wound into a number of circular loops or turns, it is called a helix. In this case, the lines of force around each turn will also embrace a number of other turns. By winding the turns very close together, a large number of lines of force will encircle the entire helix, in which case a strong field will exist within it. If the ratio of length to diameter is great, the helix is called a "solenoid." A helix or solenoid has magnetic properties and acts like any other magnet. The direction of the current in the helix will determine which end will be the north and which will be the south pole. If the helix is grasped with the right hand, so that the fingers are in the direction of the current flow, the thumb will point towards the north pole.

(b) *Laws of Magnetic Action between Current-carrying Conductors.* These are also called Maxwell's Laws:

(1) *Parallel currents in the same direction.* It can readily be seen that in this case, the lines of force surrounding

two conductors will either both be clockwise, or both counter-clockwise. In either case, the magnetic field due to one conductor will tend to weaken the field due to the other, in the space between them. Hence, the stronger fields on the outsides will tend to push the conductors together.

(2) *Parallel currents in opposite directions.* In this case, the fields between the two conductors will be in the same direction, and will merge together, thus tending to push the conductors apart.

(3) *Currents at an angle.* The magnetic fields around two

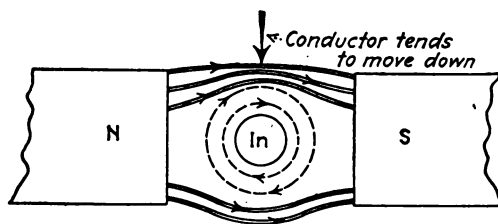


FIG. 3. — "Motor" action.

conductors at an angle will react upon each other in such a way as to tend to bring the conductors parallel, and with the current flowing in the same direction.

(c) *Maxwell's Law of Motor Action.* A conductor, carrying a current whose direction of flow is at right angles to a magnetic field, will tend to move out of this field. The cause of this is the interaction between the magnetic field and the field surrounding the current-carrying conductor. There is a fixed relationship between the direction of the magnetic force tending to move the conductor, and the directions of the magnetic field and the current in the conductor. This can be seen by reference to Fig. 3. A cross-

section of a conductor is represented, with current flowing inward, at right angles to the direction of the magnetic field. Since the current is flowing in, the lines of force due to this current are in a clockwise direction about the conductor. Hence, their direction is the same as the main field above the conductor, and hence they combine there to form a strong field. Below the conductor, the lines of force due to the current are in the opposite direction to those of the main field, and therefore the field is weakened. As a result, the relatively stronger field above the conductor pushes down on it, thus tending to move it downwards, in a direction at right angles to the direction of current flow and to the direction of the magnetic field. This law is the fundamental principle of operation of direct-current motors, and also of certain electrical meters. An extension of the fundamental principle, states that "every current-carrying conductor, or system or conductors, tends to change its shape or position, so that it will embrace the maximum number of lines of force in a positive direction." Thus, in the electric motor, the current-carrying coil tends to take such a position, that the magnetic field enclosed by it will be as great as possible, and all in the same direction.

(d) *Law of Generator Action.* This is also known as the law of "Electromagnetic Induction," and as "Faraday's Law."

(1) *Statement of law.* If there is relative motion between an electrical conductor and a magnetic field, such that the conductor cuts flux, an e.m.f. will be induced in the conductor.

(2) *Magnitude of induced e.m.f.* The amount of the induced e.m.f. will depend upon the strength of the magnetic field, upon the speed of cutting, upon the length

of the conductor cutting the field, and upon the direction of motion between the conductor and the field. Thus, the stronger the magnetic field, the greater the induced e.m.f. The induced e.m.f. will also increase with increased speed of cutting and with increased conductor length. When the conductor cuts the flux at right angles, the induced e.m.f. is maximum. If the flux is cut in any other direction, the induced e.m.f. will be less. The induced e.m.f. decreases from maximum to zero, as the angle of cutting decreases from 90 degrees to zero degrees. If a conductor is of such length, and moves in such a direction, and at such a speed, as to cut 100,000,000 lines of force in a second, one volt will be induced in it.

(3) *Value of induced e.m.f. expressed as an equation.* The elements which determine the value of the induced e.m.f. may be expressed as an equation. Such an equation is useful for purposes of calculation. Thus:

Induced e.m.f. (in volts)

$$= \frac{\text{Flux Cut (in lines or maxwells)}}{\text{Time (in seconds)} \times 100,000,000} \dots\dots \text{Equation (15)}$$

The above equation refers to the average value of the e.m.f. induced in a single conductor. If a number of conductors are used, the same e.m.f. will be induced in each. If they are so connected that their e.m.f.'s add up, the total average e.m.f. can be found by multiplying equation (15) by the number of conductors.

(4) *Numerical example.* If a conductor moves across a flux of 2,000,000 lines in $\frac{1}{2}$ second, what is the average value of the induced e.m.f.? From equation (15):

$$\frac{2,000,000}{\frac{1}{2} \times 100,000,000} = 0.04 \text{ volt.}$$

To find the voltage between the terminals of a coil of 1000 turns, one side of which cuts 2,000,000 lines in $1/10$ th second. From equation (15):

Induced e.m.f. for one turn

$$= \frac{2,000,000}{1/10 \times 100,000,000} = 0.2 \text{ volt.}$$

Hence, for 1000 turns, induced e.m.f. = $1000 \times 0.2 = 200$ volts.

(5) *Direction of current flow.* When an e.m.f. is induced in a conductor, and this conductor forms a closed circuit, a current will flow. In all cases of electromagnetic induction there is a fixed relation between the direction of the magnetic field, the direction in which the conductor cuts this field, and the direction of current flow. This relation can best be remembered by means of the right-hand rule, which states that if the right hand is held open, with thumb extended, so that the palm of the hand is towards the north pole of the magnet (i.e., so that the lines of force enter the palm), and the thumb points in the direction of the conductor's motion, then the fingers will point in the direction of the current flow.

(e) *Lenz's Law.* Whenever current flows in a conductor, due to electromagnetic induction, the action between the magnetic field which is being cut and the field around the conductor is always such as to tend to oppose further motion of the conductor. Fig. 4 explains the reason for this action. A portion of a closed magnetic circuit is shown — the north and south poles. An electrical conductor which forms a closed circuit, is moved downward between the north and south poles, so as to cut flux. According to the

right-hand rule, stated above, the direction of the current flow will be towards the observer. Hence, according to the rule given under 3 (a) (1), the direction of the magnetic field around the conductor will be counter-clockwise. Hence, as can be seen from the directions of the arrows, the two fields will merge together and form a strong field in the

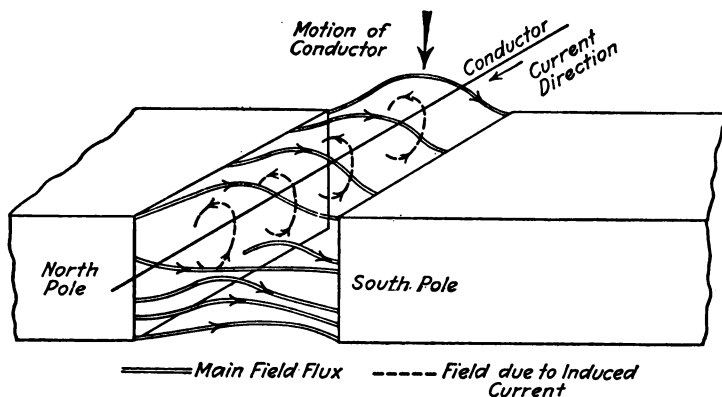


FIG. 4. — Action between main field flux and field due to induced current, accounting for Lenz's Law.

path of the conductor, while in the rear of its path, the fields will oppose each other. This thickening of the field directly ahead of the conductor explains the magnetic opposition offered to further motion. Lenz's Law may also be stated in the following form: The field due to an induced current always acts to prevent a change of the original field.

Outline of Lesson 3 — ELECTRICAL AND MAGNETIC CIRCUITS

1. ELECTRICAL CIRCUITS:

(a) Materials:

- (1) Conductors.**
- (2) Non-conductors and Insulators.**

(b) Properties of Electrical Circuits:

- (1) Resistance.**
- (2) Inductance.**
- (3) Capacity.**

(c) Properties determining Resistance: (neglecting temperature change):

- (1) Unit resistance of various materials.**
- (2) Effect of variation of dimensions.**
- (3) Meaning of "circular mil," and "mil-foot."**
- (4) Variation of resistance expressed as an equation.**
- (5) Numerical example.**

(d) Effects of Temperature on Resistance:

- (1) Meaning of "temperature coefficient" of resistance.**
- (2) Effect of temperature expressed as an equation.**
- (3) Numerical example.**

(e) Current-Carrying Capacity:

- (1) Current capacity limited by allowable Temperature Rise.**
- (2) Factors determining Temperature Rise.**
- (3) Factors determining Heat Generated.**
- (4) Factors determining Heat Dissipated.**
- (5) Safe Carrying Capacities.**

(f) Circuit Connections:

- (1) Open circuit**
- (2) Closed circuit.**
- (3) Short-circuit.**
- (4) Series circuit.**
- (5) Parallel circuit.**
- (6) Series-parallel circuit.**
- (7) Network.**

(g) Circuit Calculations:

- (1) Open circuit.**
- (2) Series circuit.**
- (3) Parallel circuit.**
- (4) Series-parallel circuit.**
- (5) Network.**

2. MAGNETIC CIRCUITS:

(a) Materials:

- (1) Magnetic.**
- (2) Non-magnetic.**

(b) Reluctance of Magnetic Materials:

- (1) Variation with flux density.**
- (2) Variation with material.**
- (3) Variation with dimensions.**
- (4) Variations of reluctance expressed as an equation.**
- (5) Numerical example.**

(c) Reluctance of Non-magnetic materials.

- (1) Variation with dimensions.**
- (2) Variations of reluctance expressed as an equation.**
- (3) Numerical example.**

(d) Effects of Changing Magnetism:

- (1) Hysteresis.**
- (2) Eddy currents.**

(e) Circuit Connections:

- (1) Series.**
- (2) Parallel.**
- (3) Series-parallel.**

(f) Circuit Calculations:

Numerical Example.

LESSON 3. — ELECTRICAL AND MAGNETIC CIRCUITS

1. Electrical Circuits

(a) *Materials:*

(1) *Conductors.* Materials which offer a relatively easy path for the flow of electricity are called “conductors.” In general, the metals are of this class, copper wire being usually used as a low-resistance conductor.

(2) *Non-conductors and Insulators.* There are no non-conductors of electricity, but certain materials are such poor conductors, that they may be classed as non-conductors. When such non-conductors are used to keep an electric current in a predetermined path (that is, in a conductor provided for that purpose), they are termed “insulators.” Hence, the function of the insulator is to prevent appreciable current leakage. Where non-conductors are used primarily to withstand the application of high voltage, they are termed “dielectrics.” The terms insulator and dielectric both apply to non-conductors. Hence, the classification of a non-conductor as an insulator, a dielectric, or both, depends upon the purpose for which it is used. Ebonite, paraffin, and flint glass are classed among the best insulators. Ebonite, rubber, and gutta percha are among the best dielectrics. Conductors are insulated with cotton or silk in the smaller sizes, cables being usually insulated with rubber-insulating compound.

(b) Properties of Electrical Circuits:

(1) *Resistance.* As explained in a previous lesson, every conductor offers a certain amount of resistance to the flow of current. The unit of resistance is the ohm, but high resistances, such as insulation resistances, are measured in "megohms." A megohm is equivalent to a million ohms. For extremely low resistances, the "microhm" is used. This is equivalent to one one-millionth of an ohm. The way in which resistance affects the flow of current has been fully explained under "Ohm's Law."

(2) *Inductance.* Every electric circuit possesses a certain amount of inductance. This property only manifests itself when the current in the circuit changes. Inductance is the property of an electrical circuit which determines the value of the induced e.m.f. in that circuit, when current is changed at a definite rate. The unit of inductance is the "henry," but as most inductances measured are considerably smaller than the henry, the millihenry is usually employed. This is equal to one one-thousandth of a henry. A term which is sometimes used instead of inductance, and which means exactly the same thing is "coefficient of self-induction." The best way to understand the property of inductance is to go back to fundamental laws. It has been stated under "Electromagnetic Laws," that whenever there is relative motion between a conductor and a magnetic field, such that lines of force cut, or are cut by, the conductor, an e.m.f. will be induced. This is exactly what happens in any conductor when there is a change of current in it. To analyze this statement, take the case of a conductor in which current is increasing. Of course, if there is current flowing, there will be a mag-

netic field around the conductor. Also, as the current increases, the strength of the magnetic field increases. It is convenient to consider the increased number of lines of force, as coming from the very center of the conductor. In this case, the lines of force *must cut* the conductor as they spread out and encircle it. Here then, is the relative motion between the conductor and the flux, and hence, according to Faraday's Law, an e.m.f. must be induced. The direction of this induced e.m.f., in accordance with Lenz's Law, will be such as to tend to prevent further increase of current. This can easily be verified by means of the right-hand rule.

Now, consider the case of a current decreasing in a conductor. The magnetic field decreases also. In this case, think of the lines of force as shrinking into the very center of the conductor as the field becomes weaker. Here again, there is relative motion between the conductor and the flux and hence an e.m.f. must be induced. In this case, the direction of the induced e.m.f. will be such as to tend to prevent further decrease.

In other words, the direction of an e.m.f., induced through a changing current, will always be such as to oppose further change. This is simply another way of stating Lenz's Law.

The above discussion explains why an e.m.f. will be induced in a conductor when current in that conductor changes. The e.m.f. will be a counter-e.m.f. if the current is increasing but will be in the same direction as the current if the current is decreasing. The reason for this, is that in one case the lines of force are expanding, while in the other they are shrinking inwards, and hence the

relative motion between flux and conductor is in different directions in the two cases.

The value of the induced e.m.f. will depend in part on the rate of change of the current (equivalent to the speed of cutting). However, although the current is changed at the same rate in two different circuits, say at the rate of one ampere per second, it may be found that the induced voltage in the two circuits is different. If one volt is induced in one of the circuits, and two in the other one, in the above case, the first circuit would have an inductance of one henry, while the second circuit would have an inductance of two henrys. This explains the definition given above, that the inductance is a property of the circuit which determines the value of the induced e.m.f., when current is changed at a definite rate. Why then, did the one circuit have an inductance of two henrys, while the other one had only an inductance of one henry? What property of the circuit caused one volt to be induced in one case, and two volts in the other, when the current itself changed at the same rate in each circuit? By going back to fundamental principles again, the answer to this will be apparent. It has been shown that in any case, where an e.m.f. is induced, its value will be determined by various other things, aside from the rate of cutting. The strength of the magnetic field is one of the things determining the value of the induced e.m.f. The length of conductor cutting the field is another. Hence, any arrangement of a circuit in which current is changing, which will cause more lines of force to be cut (either by an increase of field strength or by an increased length of conductor in the field) will thus cause a higher induced voltage and hence a higher *inductance*.

This explains why a conductor wound into a helix will have greater inductance than the same conductor unwound and straight. The field within the helix will be concentrated (as explained under "Electromagnetic Laws" par.— 3 (a) (2)). Also more turns of the helix will cut flux. This is equivalent to an increased length of conductor cutting the magnetic field. To illustrate this, take the case of an increasing current. As the lines of force spread out from the center of the conductor, they cut many turns, instead of simply cutting the conductor once. Hence a much larger e.m.f. will be induced. If the helix has an iron core instead of an air core, the inductance will be still further increased. In this case, a much better magnetic path is provided for the lines of force. This increases the strength of the magnetic field, thus again increasing the induced e.m.f. Therefore, it can be seen, that although inductance is a property of the electrical circuit, it also depends to a certain extent, upon the magnetic properties of the substance or substances in the immediate vicinity of the electrical circuit. If this is of high reluctance, such as air, then the inductance will be much lower than if the substance is of a low reluctance such as iron. Since permeance (ease of magnetic flow) is the reciprocal of reluctance, it may be easier to remember that the greater the permeance of the associated magnetic circuit, the greater the inductance of the electrical circuit. This again, merely depends upon the fundamental principle, that a higher e.m.f. will be induced if a stronger magnetic field is cut.

It is possible to calculate the e.m.f. which will be induced in a given electrical circuit, when current changes

in value, provided the rate of change of the current and the inductance of the circuit are known. The inductance of the circuit can be calculated if the induced voltage and the rate of change of current are known. The equation connecting these is as follows:

$$\text{Induced e.m.f. (in volts)} = \text{Inductance (in henrys)} \times \text{Rate of Change of Current (in amps. per sec.)} \dots \text{Equation (16)}$$

Numerical example. A circuit which possesses an inductance of 10 millihenrys and carries a direct current of 200 amperes is broken within one fifth of a second. To find the average voltage induced in the circuit during this interval of time: From equation (16)

$$\text{Av. Voltage} = 10/1000 \times \frac{200}{1/5} = 10 \text{ volts.}$$

The way in which inductance affects the flow of current in an electrical circuit may be summed up as follows: The greater the inductance of a circuit, the greater will be the opposition offered to a change of current.

(3) *Capacity.* Every electrical circuit possesses a third property called "capacity." The more modern names for capacity are either "capacitance," or "permittance." This property does not manifest itself unless there is a change of voltage. Since voltage changes must always be accompanied by current changes, capacity effects are especially noticeable where alternating or other changing currents are used. The greater the capacity of a circuit, the greater will be the opposition offered to a change in voltage. Capacitance depends for its action upon the fact that every electrical circuit possesses to some de-

gree, the ability to hold a certain quantity or charge of electricity, after the removal of the source of supply. However, unless the circuit is specially designed and suitably insulated, for this purpose, its ability to hold a charge of electricity will be extremely small. Electricity which is stored in a circuit in this manner is sometimes referred to as "static electricity." The kinetic energy of the current electricity is changed for a short period of time to the potential energy of static electricity. The ability of a conductor or a circuit to hold an electrical charge will depend upon its size, shape, arrangement, and nearness to other conductors. An arrangement of conductors, specially designed for the purpose of holding a charge, is referred to as a "condenser." A condenser usually consists of two metal plates, of large area, and as close together as possible, but separated by a dielectric. The dielectric must have the power to resist puncture due to the potential difference between the plates. Since the dielectric is classed as a non-conductor, such an electrical circuit is an "open" circuit, in d.c. work, and hence is of relatively small importance, in so far as the study of elementary electrical engineering is concerned. This statement also applies to the property of capacitance itself. However, in the more advanced alternating-current work, both capacitance and inductance are of extreme importance, and hence it is necessary to comprehend the actual meaning of these properties, before proceeding to more advanced work. As explained under "Electrical Units," the unit of capacity is the farad. Since this is too large for ordinary work, the term microfarad, which means millionth of a farad, is usually

used. If a coulomb of electricity (an ampere-second) raises the potential of a circuit one volt, that circuit has a capacity of one farad. The relation between coulombs, voltage and capacitance can be expressed as an equation:

Quantity of electricity (in coulombs)
 = Capacitance (in farads) $\times$ E.m.f. (in volts). . Equation (17)

Numerical example. To find the coulombs of electricity which a condenser of 10 microfarads capacity will hold, when the pressure between its terminals is 300 volts. From equation (17):

$$\text{Quantity} = 10/1,000,000 \times 300 = 0.003 \text{ coulomb.}$$

It is possible to draw a rather close analogy between certain mechanical properties and between the properties of the electrical circuit. To illustrate, assume the case of several freight cars, disconnected from the locomotive, rolling along a level track, with gradually decreasing speed, and finally being brought to a standstill by a bumper at the end of the track or siding. In this case, the "friction" between the wheels and the track causes the train of cars to slow down, consuming energy, which is converted into heat. The "inertia" of the moving cars tends to keep them in motion (just as it would tend to keep them at rest if they were at a standstill). The "elasticity" of the bumper allows it to be displaced by the pressure of the collision, and thereafter, to return to its original shape, thus exerting a back pressure against the train of cars, thus bringing them to a stop, with but a small loss of energy.

To show the analogy between the above mechanical illustration, and an electrical one, assume an electrical

circuit of rather high resistance (say, a long, small-diameter wire), of high inductance (many turns wound around an iron core) and of high capacity (assume a condenser in the circuit). Assume that a decreasing current is flowing in the circuit, and that the voltage varies from a maximum value to zero in a certain short interval of time. (NOTE: This analogy could be drawn as easily for an increasing current.) The electrical resistance of the circuit is analogous to the mechanical friction, since energy is converted into heat. The inductance of the circuit is analogous to inertia, since it tends to oppose the change of current value; in this case, to prevent its decrease. There is no loss of energy due to inductance, but its effect is brought about through the energy of the magnetic field. The capacity of the circuit is analogous to elasticity. It causes the condenser to discharge as soon as the voltage starts to become smaller. This tends to oppose the decreasing pressure (that is to oppose a change of voltage) with the result that the capacity e.m.f. retards the dying down of the current. An electrostatic stress or displacement takes place in the dielectric of the condenser when it is charged. This is analogous to the displacement of the bumper, in the mechanical illustration, upon collision. When the condenser is discharged, the displacement in the dielectric is relieved and it returns to its original condition. Its return to this condition may be considered as due to its electrical elasticity just as the return of the bumper to its original shape is due to its mechanical elasticity. In both the mechanical and the electrical cases, energy which was stored for a short period of time is again returned to the circuit.

There is no loss of energy due to capacity, since the energy which is stored in the condenser (energy used to cause a displacement of the dielectric) is later practically all returned to the circuit when the condenser discharges.

From the above discussion, it may be seen that the effects of inductance and capacity upon the current flowing in an electrical circuit are exactly opposite. While the inductance of a circuit will tend to prevent current from building up or dying down, capacity will have exactly the opposite effects. Hence, by properly combining capacity and inductance in electrical circuits, it is possible to neutralize the effects of one by means of the other. A simple illustration of this fact will be given. In certain types of electrical apparatus, it is necessary to make and break a circuit of high inductance, with great rapidity (vibrator of Ruhmkorff coil). As the circuit is broken, the inductance tends to prevent the dying down of the current, by means of the high self-induced e.m.f. The result is, that the e.m.f. of self-induction acts in the same direction as the impressed e.m.f., at the instant that the vibrator breaks the circuit, and there is a rush of current which results in an objectionable arc or spark. To prevent this, a condenser is connected between the terminals of the vibrator. Hence, when the vibrator closes the circuit, the condenser can have no charge, since its plates are connected together and at the same potential. As soon as the vibrator opens the circuit, the condenser immediately becomes charged, but since the voltage is decreasing, the condenser discharges during the short interval of time necessary for the e.m.f. to reach zero value. The discharging e.m.f. is

opposed to the direction of the decreasing e.m.f., and hence it tends to prevent dying down of the current. The net result is that the action of the inductance is neutralized by that of the capacity, since the e.m.f. of self-induction is increasing in one direction (that of the current flow), while the capacitance or discharge e.m.f. is increasing in the opposite direction. Therefore, sparking due to the high inductance is eliminated.

(c) *Properties determining Resistance* (neglecting temperature change):

(1) *Unit resistance of various materials.* The material of a conductor has an important bearing upon its resistance. Thus a unit length and unit cross-section of aluminum has about one and one half times the resistance of copper having the same dimensions. Platinum has about six times the resistance. This difference of resistance of unit length and unit cross-section of various conductors, is sometimes expressed by saying that each conductor has a certain "specific resistance," or "resistivity." Both these terms mean the same thing as unit resistance (do not confuse with "unit of resistance") and refer to the resistance in ohms of unit length and unit cross-section of the material. Unit resistance may be measured in ohms per inch cube, but more commonly it is measured in ohms per mil-foot. (The meaning of mil-foot will be explained later.)

(2) *Effect of variation of dimensions.* The longer a conductor, the greater its resistance, while the greater its cross-sectional area, the less its resistance. The length of a conductor is usually expressed in feet, while the cross-sectional area is usually expressed in circular mils (equivalent to diameter in mils multiplied by itself).

(3) *Meaning of "circular mil," and "mil-foot."* A "circular mil" is a common unit of area for circular cross-section electrical conductors. It is equal to the area of a circle, one mil (.001 inch) in diameter. Since the area of a circle is 0.7854 times the diameter squared, hence the area of a circle, of a cross-section of a circular mil, expressed in square inches, $= 0.7854 \times 0.001 \times 0.001 = 0.000,000,785,4$ square inches. Hence, a circular mil is a unit of area more than a million times smaller than a square inch (1,274,509 to be exact). Therefore, if the area is given in square inches and it is desired to change to circular mils, it will be necessary to divide by 1,274,509. However, this will seldom be necessary, since the diameter is usually obtained or given in inches. In this case, it is simply necessary to multiply the diameter by a thousand to change it to mils. Multiplying the number thus obtained by itself (squaring) will then give the desired area in circular mils. The term "ohms per mil-foot" really means ohms per circular mil-foot, since it refers to a conductor having a cross-sectional area of one circular mil and having a length of one foot.

(4) *Variation of resistance expressed as an equation.* The various things which determine the resistance of a conductor, may be expressed as an equation, thus:

Resistance in ohms

$$= \frac{\text{Length (in feet)} \times \text{Resistivity (in ohms per inch cube)}}{\text{Cross-sectional Area (square inches)}}$$

Equation (18)

The above equation can also be expressed in the following terms:

Resistance (in ohms)

$$= \frac{\text{Length (in feet)} \times \text{Resistivity (in ohms per mil-foot)}}{\text{Diameter (in mils)} \times \text{Diameter (in mils)}}$$

Equation (19)

(NOTE: As explained above, the diameter squared, in mils, is the same thing as the area in circular mils.)

(5) *Numerical example.* To find the resistance of a copper wire, at room temperature, 1000 feet in length, one-tenth inch in diameter. The resistivity, as obtained from an electrical handbook = 10.5 ohms per mil-foot at 75 degrees Fahrenheit.

From equation (19), Resistance in Ohms

$$= \frac{1000}{(1/10 \times 1000) \times (1/10 \times 1000)} \times 10.5 = 1.05 \text{ ohms.}$$

The above problem refers to No. 10 copper wire (Brown & Sharpe or American Wire Gauge). It can conveniently be remembered that No. 10 copper wire has an approximate diameter of 0.1 of an inch, and that 1000 feet of such wire have an approximate resistance of 1 ohm. It is possible to calculate the approximate resistances of copper wire (Brown & Sharpe or American Wire Gauge) from the above. Thus, for wires larger than No. 10, the resistance is halved for every third number of larger wire. As an example, No. 7 has an approximate resistance of $\frac{1}{2}$ ohm per 1000 feet; No. 4 has an approximate resistance of $\frac{1}{4}$ ohm per thousand feet, etc. In like manner, for wires smaller than number 10, the resistance is doubled for every third number of smaller wire. Thus, the resistance of No. 13 is approximately 2 ohms per thousand feet; of No. 16 is approximately 4 ohms per 1000 feet, etc.

The two numbers between every third may be calculated from the others, since the first smaller size between has about 1.25 greater resistance, while the second smaller size has about 1.6 greater resistance. Thus, the resistance of No. 11 wire is approximately $1 \times 1.25 = 1.25$ ohms per thousand feet; that of No. 14 is approximately $2 \times 1.25 = 2.5$ ohms per 1000 feet. The resistance of No. 12 wire is approximately $1 \times 1.6 = 1.6$ ohms per 1000 feet; that of No. 15 is approximately $2 \times 1.6 = 3.2$ ohms per 1000 feet; etc.

(d) *Effects of Temperature on Resistance.* The resistance of practically all electrical conductors increases with increase of temperature.

(1) *Meaning of "temperature coefficient" of resistance.* The term "coefficient" refers to a number used as a multiplier. The temperature coefficient is that multiplier, which will give the increase in resistance, per degree rise in temperature, for each ohm of the material. For all pure metals the temperature coefficient is approximately 0.0023 (where temperature is measured in degrees Fahrenheit). The temperature coefficient is not constant for all initial temperatures, but decreases slightly with increase of initial temperature. This is because the multiplier or coefficient does not have to be as large at higher initial temperatures to show the proportional increase of resistance for each ohm, since the resistance itself is higher at a higher temperature. However, the coefficient 0.0023 is close enough for ordinary work.

(2) *Effect of temperature expressed as an equation.* If the initial resistance in ohms is multiplied by the change in temperature and by the temperature coefficient, the

change in resistance will be obtained. If this is added to the initial resistance, the result will be the final resistance. This may be expressed as an equation thus:

Final Resistance (in ohms) = Initial Resistance (in ohms) $\times$ Change in Temperature (in degrees Fahr.) $\times$ 0.0023 plus Initial Resistance (in ohms) Equation (20)

(3) *Numerical example.* To determine the resistance of a circular mil-foot of annealed copper wire, at a final temperature of 68 degrees Fahrenheit, if its resistance at 32 degrees Fahrenheit = 9.59 ohms.

From equation (20):

$$\begin{aligned}\text{Final Resistance} &= 9.59 \times (68 - 32) \times 0.0023 + 9.59 \\ &= 10.38 \text{ ohms.}\end{aligned}$$

(e) *Current-carrying Capacity:*

(1) *Current capacity limited by allowable Temperature Rise.*

The allowable rise in temperature of the conductors of an electrical circuit is the final factor which determines the current-carrying capacity. If the conductors are insulated, the maximum allowable temperature of the insulation will impose the limitation, since the insulation will deteriorate and smoke, char, or even burn, if at too high a temperature. Thus, rubber-insulated cables should not be worked above 158 degrees Fahrenheit; paper-insulated cables should not be worked above 194 degrees Fahrenheit, etc. If the conductors are bare, fusing temperature may determine the maximum safe temperature limit, or the allowable final temperature of other substances in the immediate vicinity may determine the maximum temperature.

(2) *Factors determining Temperature Rise.* The tempera-

ture rise will be determined by the difference between the heat generated and the heat dissipated or removed. Thus, a certain amount of electrical energy will be converted into heat. Some of this heat will be carried away. The remaining heat will serve to increase the temperature. Of course, a certain amount of heat energy will raise the temperature of some materials a great deal more than others. Hence the material of the conductor will also have some bearing on the temperature rise, aside from its resistance.

(3) *Factors determining Heat Generated.* The heat generated in an electrical circuit will depend upon the value of the current flowing and upon the resistance of the conductors. If the current is doubled, the heat generated will be quadrupled. If the resistance is doubled, the heat generated will simply be doubled. Thus, an increase of current has a much greater effect on the amount of heat generated than a proportionate increase of resistance. It should be noted, that anything which will increase the resistance of a conductor, or of a circuit, will increase the amount of heat generated. Thus, since some materials have greater unit resistance than others, they will generate more heat in the same ratio, and hence will have a correspondingly lower current-carrying capacity. This explains why platinum, which has about 6 times the resistance of copper, will generate 6 times the amount of heat. The longer a conductor, the greater its resistance, and hence the greater the heat generated. The smaller its cross-section, the greater its resistance also. Since the cross-section changes with the square of the diameter ($\text{Area} = .7854 \times \text{Diameter}^2$), if the diameter is halved, the

resistance, and therefore the heat generated, will be increased four times. The type of circuit connection determines total resistance and hence affects the amount of heat generated. Thus, a "parallel" connection provides more paths for the current than a "series" connection, and hence has less resistance. The various types of circuit connections will be discussed in paragraph (f). The amount of heat generated will also depend directly upon the duration of time during which the current is flowing. It has been shown, under "Laws of Electrical Heating," that the heat generated, due to the flow of an electric current, when measured in B.T.U.'s, is equal to the square of the current (in amps.), times the resistance of the circuit (in ohms), times the time during which the current flows (in seconds), divided by 1055. (See equation (11).) If no heat were dissipated or carried away, the temperature rise could easily be calculated from equation (11), by dividing the total heat generated, in B.T.U.'s, by the product of the mass of the conductor, in pounds, times its specific heat. A numerical illustration of this is given under equation (11). However, the actual temperature rise will not be as great as this, since a certain amount of the heat will be dissipated. The temperature of the circuit will become constant when the rate of generation of heat is equal to the rate at which heat is conveyed away by conduction, convection, and radiation.

(4) *Factors determining Heat Dissipated.* As stated above, heat may be dissipated, or conveyed away from the conductor by conduction, convection or radiation. "Conduction" refers to the transfer of heat from one particle of a substance to another, or from one substance to another

one, which is in contact with it. The removal of heat by means of conduction within the conductor itself is exceedingly small. It can be neglected, in estimating the loss, in the case of long conductors. However, where the conductor is insulated, heat will be dissipated by conduction from the conductor to the insulation and thence through the insulation. The removal of the heat from the outside surface will depend upon radiation or convection. The amount of heat removed by conduction through the insulation will depend, in general, upon the material of the insulation and on its thickness. Thus, for example, rubber will conduct heat better than dry or saturated paper. If thicker insulation is used, less heat will be conducted away in a given time, but the use of a thick instead of a thin insulation will cause only a slight decrease in the amount of heat conducted away.

“Convection” in this case, refers to a circulation of the heated air or other surrounding gas upwards from the conductor. Convection takes place naturally since the heated particles are lighter than the cold ones. (Not only gases, but also liquids expand when heated, thus becoming lighter per unit of volume.) Hence there is a strong tendency for convection currents to flow continuously, carrying the heated air away and being replaced by colder air. Convection is assisted artificially by proper ventilation or in special cases by blowers. The amount of heat removed by convection will depend upon whether the conductor is bare or insulated, upon whether it is indoors or out and especially upon the kind of ventilation afforded the conductor and the circuit. Thus the ventilation will be better with a single conductor

than if there are several conductors in a cable; the ventilation is better in a long straight circuit than in one consisting of a compact coil; better in a solid conductor than in a stranded one, etc. The heat removed by convection will also depend upon the nature of the surrounding medium (whether air, hydrogen, oil, water, etc.,) and upon the ability of this medium to dissipate the heat. The larger the conductor, the greater the surface available for convection. The heat removed will decrease, as the temperature of the surrounding medium approaches that of the conductor.

“Radiation” here refers to a removal of heat from the circuit, which is independent of the nature of the medium surrounding the conductors, and which occurs regardless of conduction or convection. The heat is absorbed by colder bodies which are not in direct contact with the hot conductor, and the transfer takes place without heating the intervening medium. Radiated heat travels in straight lines. The amount of heat radiated depends upon the difference in temperature between the conductor and the colder body absorbing the heat. It also depends upon the material of the surface radiating the heat and upon the amount of surface exposed and its nature (that is, whether rough or smooth). The amount of heat lost by radiation increases with extreme rapidity as the difference in temperature between the radiating conductor and the absorbing substance is increased. Thus, if the difference of temperature is doubled, the heat radiated is increased sixteen times. However, since the temperature differences are usually not very great, the heat removed by radiation is small as compared with that dissipated by convection.

Rough surfaces will radiate more heat than smooth ones.

(5) *Safe Carrying Capacities.* It can be seen, from the above discussion, that the maximum current which a conductor can carry safely, is dependent upon a large number of widely varying factors. In general, a conductor of larger cross-section will have greater current-carrying capacity, but it should be noted that some factors are not affected to as great a degree as others, with increased cross-sectional area. The greater the area, the less the resistance, and hence the less the heat generated. The greater the circumference the greater the surface offered for heat transfer, and hence the greater the heat dissipated. Both the area and the circumference depend upon the diameter, but the area increases with the square of the diameter, while the circumference only increases directly. Thus, if the diameter is doubled, the area will be quadrupled, and only one fourth as much heat will be generated. However, doubling the diameter only doubles the circumference, and hence the amount of heat dissipated will not be quadrupled, but only doubled. This accounts for the fact that the current per square inch or per circular mil of a conductor must be much less for a large conductor than for a small one, for the same rise in temperature under similar conditions. The safe carrying capacities of different conductors, under various conditions of insulation, for various sizes, for various uses, etc., have been tabulated and are contained in practically all electrical engineering handbooks. Since these values are obtained as a result of exhaustive experiment and research, their use is preferable to a calculation, especially in view of the numerous factors involved.

(f) *Circuit Connections:*

(1) *Open circuit.* An open circuit is an electrical circuit which does not offer a complete path for the flow of electricity. There may be one or more breaks in the path.

(2) *Closed circuit.* A closed circuit is an electrical circuit which allows current to flow and thus permits the transference of electrical energy. In general, all electrical circuits contain a source of electrical energy, a path for the transmission of this energy, and a device for its utilization. In addition, electrical circuits usually contain means of controlling and measuring the electrical energy.

(3) *Short-circuit.* A short-circuit usually refers to a condition of an electrical circuit, whereby an external path of very low resistance is suddenly connected across the source of electrical energy. A short-circuit, therefore, is accompanied by a large increase in current. Since this is extremely undesirable, the effects of short-circuits are guarded against by protective devices, such as "circuit breakers," or "fuses," which operate automatically, in case of a short-circuit (or in case of any overload) and produce a break in the circuit. (That is, produce an open circuit.)

(4) *Series circuit.* When two or more parts of an electrical circuit are so connected that the same current flows through them, they are said to be in series, and the circuit is called a series circuit. Such a circuit may be likened to a steam circuit, in which steam which has been used in a high-pressure engine is passed on to an engine workable at a lower pressure. In electrical terms, we would say that the two engines are in series with each

other. The same steam which flows through one engine, flows through the other. In its passage through each, a certain amount of energy is taken away from the steam, and there is a certain pressure drop depending upon the work which has been done. This also applies to an electrical circuit which is in series. The same current flows through all the parts, but each part takes away a certain amount of energy and there is a voltage drop through each one, depending upon the resistance which must be overcome and upon the value of the current flowing. The fact that the same current flows through all parts of an electrical circuit which are in series, is in accordance with "Kirchhoff's First Law." As explained under "Electrical Laws," this states that the current flowing away from a point must equal the current flowing towards that point. Since, at all points of a series circuit, there is only the one path for the current, the current throughout the circuit must be the same. The voltage drop through the various parts of the circuit is dependent upon Ohm's Law. (See, equation (2). The total resistance of various parts of a series circuit is equal to the sum of the separate resistances. Thus if the resistance of one of the leads to an electrical device is 5 ohms, the resistance of the device itself is 200 ohms, and the resistance of the other lead is 7 ohms, the total resistance of this series circuit is equal to 212 ohms. Hence, if it is desired to calculate the voltage necessary to send a certain current through a series circuit, by means of Ohm's Law, it will be necessary to add up the separate resistances and multiply their sum by the value of the current required. If sources of electrical energy are connected in series, so that the

positive terminal of one connects to the negative terminal of the other (so that they are aiding each other), then the total voltage will equal the sum of the separate voltages. If they are connected in series, so that the positive terminal is connected to positive terminal (opposing each other), then the total voltage will be the difference between the opposing voltages. This will be taken up in detail under "Primary Cells."

(5) *Parallel circuit.* When two or more parts of an elec-

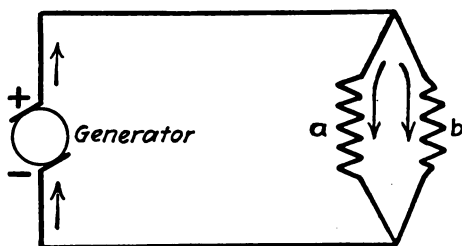


FIG. 5. — A parallel circuit.

trical circuit are so connected that the current divides between them, they are said to be in parallel and the circuit is called a parallel one. Other names which mean practically the

same thing are "multiple circuit," "divided circuit," and "shunt circuit." In a parallel circuit several branches will be connected together at the same points. (See Fig. 5.) Where a number of parts of a circuit are in parallel, the same voltage is impressed on each part. The current flowing in each branch will depend upon the impressed voltage and upon the resistance of each branch. Thus, if two parts of a circuit are in parallel, and branch *a* has twice the resistance of branch *b*, then twice as much current will flow through *b* as through *a*. The total current in a parallel circuit is equal to the sum of the currents in each branch.

As explained under "Elementary Electrical Terms,"

the name "Conductance," means the reverse of resistance and is numerically equal to one divided by resistance. It is more convenient to calculate conductances than resistances when dealing with parallel circuits. However, if the resistance is desired, simply divide the number 1 by the conductance or vice-versa. The total conductance of a parallel circuit is equal to the sum of the separate conductances of each branch. Thus, if there are three branches in parallel, and one has a conductance of 2, the other of 3, and the third of 5, the total conductance is 10, and hence the total resistance is one-tenth ohm. It should be noted, in the above case, that the resistances of the branches are $\frac{1}{2}$ ohm, $\frac{1}{3}$ ohm, and $\frac{1}{5}$ ohm respectively. It follows, that the total resistance of any parallel circuit is less than the resistance of any one of its branches. The effects of connecting sources of electrical energy in parallel will be taken up under "Primary Cells," and "Electrical Generators."

(6) *Series-parallel circuit.* Such circuits are combinations of series and of parallel circuits. The term "series-parallel" usually refers to a series circuit having certain minor branches in parallel. The term "parallel-series" usually refers to a parallel circuit having certain minor parts in series. Since Ohm's Law can be applied to a part of a circuit, as well as to the entire circuit, combination circuits such as these should be worked out for their various parts separately in determining resistances, etc. Thus, in a series-parallel circuit, in calculating the total resistance, the resistances of the various parts in series should be added up first, then the conductances of parts in parallel should be added up, the total conductance

converted to total resistance, and this should be added to the resistance already obtained. This sum will give the total resistance of the circuit. The same method applies to parallel-series circuits.

(7) *Networks*. A "network" is the term usually applied to a complicated combination of conductors making up a complete electrical circuit. (Fig. 6.) Since such a circuit is merely a more complicated arrangement of resistances in series and parallel, the total resistance can be calculated in the same way as under (6). However, where there are several sources of electrical energy in

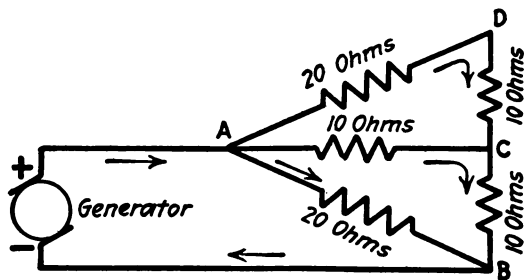


FIG. 6. — Circuit designated as a "network."

the circuit and it is desired to determine the current flowing in the various branches, it is usually necessary to apply Kirchhoff's Laws.

As an illustration of the ease with which the resistance of networks may be calculated, assume that the resistances of the various branches are as marked in Fig. 6. Assume that the current flows into the divided circuit at *A* and out at *B*. To find the total resistance between the points *A* and *B*:

Since the resistances $AD = 20$ ohms and $DC = 10$ ohms are in series, these must be added, giving a total resistance

along ADC of 30 ohms. This path is in parallel with AC . The conductance of $ADC = 1/30$ and of $AC = 1/10$, hence total conductance between A and $C = 0.133$. Hence total resistance between A and $C = 1/0.133 = 7.51$. Since this is in series with $CB = 10$ the two must be added. This gives a total resistance from A to B along the two upper paths of 17.51 ohms. But there is another path from A to B , having a resistance of 20 ohms, and these two resistances are in parallel. The conductance of the lower path $= 1/20$; that of the other $= 1/17.51$. Hence the total conductance from A to B equals the sum of these two conduct-

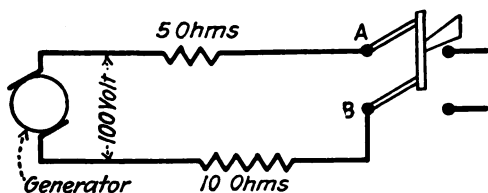


FIG. 7. — An open circuit.

ances, 0.107 and the total resistance from A to $B = 1/0.107 = 9.34$ ohms.

(g) *Circuit Calculations:*

(1) *Open circuit.* To determine the voltage at the terminals of the single-throw double-pole switch, points $A-B$, in the open circuit (Fig. 7), when 100 volts are applied at the terminals of the generator:

Since there can be no voltage drop, when no current is flowing, and since current cannot flow in an open circuit, the voltage at $A-B$ will be the same as that at the generator terminals and will equal 100 volts. The voltage as determined by a voltmeter reading, would be the same

at $A-B$ as at the generator terminals, since the very high resistance of the voltmeter would result in an extremely small current flow and thus the voltage drop in this small resistance would be negligible.

(2) *Series circuit.* To calculate the total resistance of the external circuit (that is, circuit outside of generator); to determine the current which will flow, with an applied

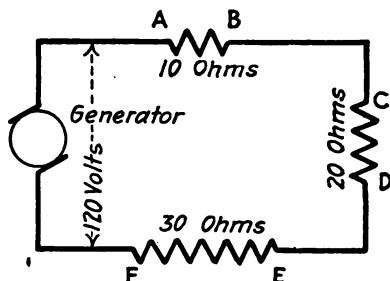


FIG. 8. — A series circuit.

e.m.f. of 120 volts; and to find voltage drop across each resistance: (Fig. 8).

In the following problems, assume that the resistance of the leads connecting resistances to generator and between resistances, equal to zero.

This can be done, since

the resistances of the leads are negligible in comparison with resistances of other parts of the circuit.

Since it is simply necessary to add the various resistances, to find the total resistance of a series circuit, this will equal 10 plus 20 plus 30 = 60 ohms.

From equation (1), Current flowing = $120/60 = 2$ amps.

From equation (2):

Voltage drop across $AB = 10 \times 2 = 20$ volts.

Voltage drop across $CD = 20 \times 2 = 40$ volts.

Voltage drop across $EF = 30 \times 2 = 60$ volts.

(3) *Parallel circuit.* To determine the total resistance of the circuit external to the generator; to determine the total current which will flow with an applied e.m.f. of

120 volts; and to determine the current which will flow in each branch: (Fig. 9).

First change all the resistances to conductances by dividing each into one. This gives the conductance of $AB = 1/10$; of $CD = 1/20$; of $EF = 1/30$. The sum of these conductances gives the total conductance; thus $1/10$ plus

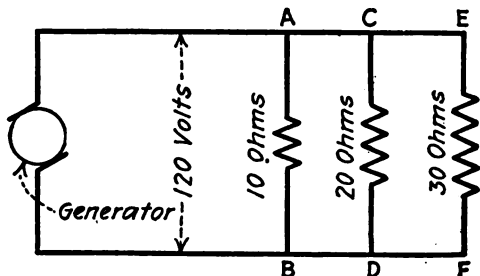


FIG. 9. — Diagram illustrating a parallel circuit problem.

$1/20$ plus $1/30 = 11/60$. Dividing this into one gives the total resistance $= 60/11 = 5\frac{5}{11}$ ohms.

From equation (1):

$$\text{Current} = 120/5.45 = 22 \text{ amps.}$$

From equation (1), but now applied to a part of the circuit:

$$\text{Current in } AB = 120/10 = 12 \text{ amps.}$$

$$\text{Current in } CD = 120/20 = 6 \text{ amps.}$$

$$\text{Current in } EF = 120/30 = 4 \text{ amps.}$$

Thus, it can be seen from the above two problems, that the same resistances give a very much smaller total resistance when connected in parallel than when in series. When in parallel, each added branch offers another path for the current flow, thus reducing the total resistance and allowing more current to flow. Adding more resistances

in parallel is equivalent to increasing the cross-sectional area of the conductor. Hence, the total resistance of a parallel circuit must be less than the resistance of any one of the branches.

(4) *Series-parallel circuit.* To find the total resistance of the circuit; to find voltage drop across each resistance; to determine the current (total) which will flow with an applied e.m.f. of 120 volts; and to find the current in the parallel branches *AB* and *CD*: (Fig. 10).

First find the conductances of *AB* and *CD* by dividing

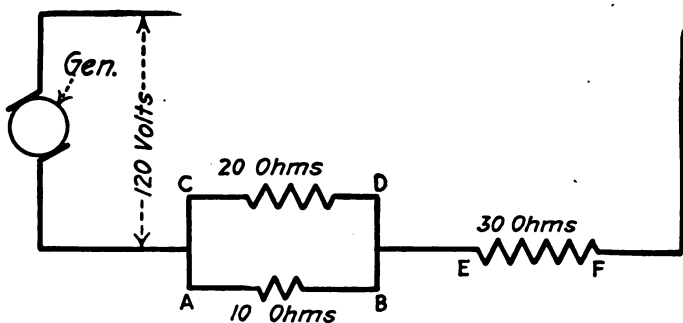


FIG. 10. — A series-parallel circuit.

each into one. Adding these will give the total conductance of the parallel circuit — thus: $1/10$ plus $1/20 = 3/20$. Hence total resistance of this circuit = $20/3 = 6.66$ ohms. Adding this to the resistance of *EF* = 30 ohms, since this is in series and a total of 36.66 ohms for the entire external circuit is obtained.

From equation (1):

$$\text{Current (total)} = 120/36.66 = 3.27 + \text{ amps.}$$

From equation (2):

$$\text{Voltage drop across } EF = 3.27 \times 30 = 98.2 \text{ volts.}$$

Since the total voltage drop in the circuit must equal the impressed voltage, the drop across AB and CD must equal the difference between 120 and $98.2 = 21.8$ volts.

Hence, from equation (1), as applied to AB :

$$\text{Current in } AB = 21.8/10 = 2.18 \text{ amps.}$$

And applied to CD :

$$\text{Current in } CD = 21.8/20 = 1.09 \text{ amps.}$$

The current in the branches AB and CD could have been determined by inspection, in this particular case, since the resistance of CD is twice AB . This means that only one-half the current will flow in CD as in AB . Hence, dividing the total current 3.27 into three parts, two-thirds will flow through AB and one-third through CD . The same answer as above will be obtained.

(5) *Network*. In the application of Kirchhoff's Laws to solving these networks and especially where more than one source of e.m.f. is involved, it is essential that the following simple conventions be used, in order to prevent confusion:

1. First: Assume a current direction for each branch of the circuit, and indicate this by means of arrow-heads. At any junction, currents toward it will be positive, those away will be negative. From Kirchhoff's First Law the sum of these positive currents must equal the sum of the negative ones, or adding equal positive and equal negative values will give zero. If a negative value of a current is obtained, in the solution of a problem, this merely indicates that wrong direction has been assumed for the current flow in that branch, and that the actual direction is opposite to that shown by the arrow-head.

Second: It is necessary to show by plus (+) and minus (-) signs the given or assumed direction in which each source of e.m.f. acts. There is a rise in voltage when passing through a source of e.m.f. from minus to plus and hence this should be taken as positive and added. Since there is a fall in voltage in passing through an e.m.f. from plus to minus, this should be taken as negative and subtracted. In working out an equation for any mesh or closed circuit, it is necessary to continue in the same direction, until completely around the circuit. Thus, if the e.m.f.'s and voltage drops are added up, and a start is made around the circuit in a clockwise direction, this direction must be continued completely around the circuit. Hence, if the current direction through a resistance is the same as that taken in working out the equation, this represents a fall of voltage and hence should be considered as negative and therefore subtracted. In like manner, if the current direction through

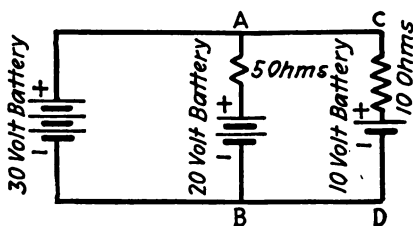


FIG. 11. — Illustration of a Kirchhoff's Law problem.

a resistance is opposite to that taken in working out the equation, this is equivalent to a voltage rise in that direction and should be taken as positive and added. The sum of the negative voltages and voltage drops,

when subtracted from the sum of the positive voltages and voltage drops, in any closed circuit or mesh, must equal zero. This is simply another way of stating Kirchhoff's Second Law.

To determine the current value and direction in branches AB and CD : (Fig. 11).

First assume current directions, and mark by arrow-heads as shown in Fig. 12. To write out an equation for the mesh or closed circuit to the left (direction of e.m.f.'s and amount of resistance given): Start at the negative side of the 30-volt battery and go around the circuit in a clockwise direction. In going from minus to plus through the battery there is a rise of voltage and hence 30 is positive and is added.

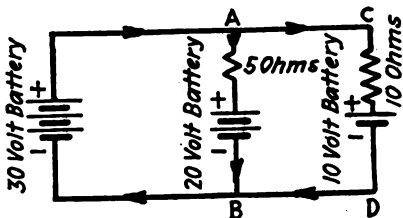


FIG. 12. — Same diagram as Fig 11, but showing by arrow-heads assumed current direction.

Since the assumed current direction through the resistance in the branch AB is the same as that being used in working the equation (i.e. clockwise), there is a voltage drop in passing through the resistance, equal to the resistance (5 ohms) times the current in the branch AB . This, then, is negative and must be subtracted. In passing through the 20-volt battery from plus to minus, there is a fall of voltage and this also is negative and must be subtracted. Hence the following equation may be written, since all the negative e.m.f.'s and voltage drops when subtracted from all the positive ones will equal zero:

$$30 - 5 \times \text{Current in } AB - 20 = 0.$$

Since the current in AB is the only unknown quantity in the above equation, it is easily seen that

$$\begin{aligned} 5 \times \text{Current in } AB &= 10 \\ \text{Current in } AB &= 2 \text{ amps.} \end{aligned}$$

Next, to find the current in CD , work out an equation for the closed circuit through the 30-volt battery and branch CD : Start again at the negative side of the 30-volt battery and go around this circuit in a clockwise direction. As before, in passing from minus to plus, there is a rise of voltage and hence the 30 is positive. Since the current direction (as assumed) is the same as that taken in working out the equation, the voltage drop through the resistance in the branch CD is negative and must be subtracted. In passing through the 10-volt battery from plus to minus there is a voltage drop and this also is negative and must be subtracted. Writing the equation as above:

$$30 - 10 \times \text{Current in } CD - 10 = 0.$$

Hence: Current in $CD = 2$ amps.

Since the current value in each answer comes out as a positive number, this shows that the correct direction of current flow in the branches AB and CD was assumed. Suppose that the current direction in AB had been assumed counter-clockwise. The same answer, 2 amps., would have been obtained as the current value in AB , but the answer would have come out as a negative value (minus instead of plus). As explained above, this would immediately show that wrong current direction had been assumed in that branch. It should be noted that although the resistance of branch AB is one-half that of CD , still the e.m.f. in AB is twice that in CD . Since in this case, the e.m.f.'s act like resistances, it is reasonable to assume that the same current will flow in each branch and this is actually found to be the case.

The total current in the circuit can easily be found, by applying Kirchhoff's First Law. The current approaching point *A* must equal the sum of the current leaving this point. The currents leaving are known—2 amps flowing through *AB* and 2 amps. through *CD*. Hence the current approaching the point *A* = 4 amps. In other words, the 30-volt battery is sufficiently strong to send a 4-ampere current through the circuit, in spite of the opposition offered by the weaker 20-volt and 10-volt batteries, and the 4 amperes divide equally, 2 flowing through *AB* and 2 through *CD*. The above equations can be proven by working out an equation for the closed circuit to the right (mesh through branches *AB* and *CD*) and using the value of current as found either for *AB* or *CD*, thus solving for the current in the other branch. If care is always taken to follow the conventions, as used above, there will be no confusion as to whether a value should be positive or negative. Hence the main difficulty in solving problems by the application of Kirchhoff's Laws will be removed.

2. Magnetic Circuits

(a) *Materials:*

(1) *Magnetic.* This refers to materials of comparatively low reluctance (i.e. materials which offer a good path for the lines of force). Such materials are often called ferro-magnetic. They include iron, steel, nickel, cobalt, manganese, chromium, magnetite, certain alloys of copper, manganese and aluminum (called Heusler Alloys), and certain other oxides. The laws governing these substances can best be set forth by means of magnetization

curves. This was explained under "Magnetic Laws." In certain types of electrical apparatus, it is possible to have a magnetic circuit, made entirely of magnetic materials. However, this is impossible in the generator, the motor, and other important apparatus. In the generator and the motor, the air-gap (necessary for mechanical clearance) forms a part of the magnetic circuit, although air is considered as a non-magnetic material. For this reason, non-magnetic materials are of importance in studying the magnetic circuit.

(2) *Non-magnetic.* For commercial purposes, air is the most important non-magnetic substance. However, practically all substances, with the exception of the ferro-magnetic ones, follow the same magnetic laws as air. Ohm's Law of the magnetic circuit applies only to non-magnetic materials. It should be remembered that while the reluctance of a non-magnetic substance is constant, the reluctance of magnetic substances varies, as the amount of flux in the substance changes. Although air, and all other substances, with the exception of the ferro-magnetic ones, are classed as non-magnetic substances, and are poor conductors of magnetic flux, when compared to iron, etc., nevertheless, they are by no means magnetic insulators. There are no substances which will prevent the passage of magnetic flux (in other words, there are no magnetic insulators or no substances which are absolutely non-magnetic). This fact introduces a certain amount of difficulty in practical magnetic circuit calculations, since it is impossible to confine all the flux into a predetermined magnetic path. Since there is no magnetic insulator, there will always be a certain

amount of flux which will serve no useful purpose. This is usually referred to as "Leakage Flux." However, the leakage flux can be reduced to a minimum by proper design of the magnetic circuit. Leakage will be reduced, if the exciting ampere-turns are distributed over the magnetic circuit so that there will be more excitation where the reluctance is higher and less where the reluctance is lower. However, in most commercial magnetic circuits, this is not practicable and other means of reducing the leakage must be resorted to. In a generator, it is customary to so design the magnetic circuit, that the path through the armature has the lowest reluctance. This results in a reduction of the leakage, since the exciting ampere-turns are concentrated at the poles and these are at a considerable magnetic distance from the armature. In general, in commercial magnetic circuits, the non-magnetic material is in series with the magnetic material. An important exception to this statement occurs in the case of leakage flux. In this case, the non-magnetic substance, air, is in parallel with the magnetic material.

(b) *Reluctance of Magnetic Materials:*

(1) *Variation with flux density.* It has been shown under "Magnetic Laws," that the reluctance of magnetic materials decreases as the flux density increases until a certain flux density has been reached (up to the point of "saturation"). At the point of saturation, the reluctance of any given material is the lowest. Thereafter, any increase of flux density will result in increased reluctance.

(2) *Variation with material.* Although all magnetic materials vary in the same way, with variation of flux density (as explained in paragraph (1)), it should be

noted that even if the flux densities are the same, various substances have widely varying reluctances. This is expressed as the "unit reluctance" of a material, and is usually referred to as "reluctivity." Hence, the reluctivity of a magnetic substance, is the reluctance of a unit length and a unit cross-section of that substance, FOR ANY GIVEN VALUE OF FIELD STRENGTH OR FLUX DENSITY. From the curves of Fig. 2 it can be seen that with the same number of ampere-turns per inch of length, there will be a very much stronger field per square inch cross-sectional area of steel than of cast iron. In other words, for any value of flux density, the reluctivity of cast iron is much greater than that of steel. Reluctivity in the magnetic circuit is analogous to resistivity in the electrical circuit. It is possible to obtain the value of reluctivity of a substance for any given flux density from the curves (Fig. 2) by dividing the ampere-turns per inch of length by the flux density, in lines of force per square inch which this excitation will produce. Or stated in another way, the number of lines of force produced in a unit cross-section of a magnetic material will equal the ampere-turns per unit length divided by the reluctivity. As explained above, the fact that the reluctivity varies with the flux density, instead of remaining constant as in non-magnetic materials, prevents the use of a simple law, such as Ohm's Law of the Magnetic Circuit. Hence the curves must be referred to. Since "permeability" is the reciprocal of reluctivity, the permeability of any substance may be found from the magnetization curves by dividing the flux density in lines of force per square inch by the ampere-turns per inch of length.

(3) *Variation with dimensions.* The reluctance of any magnetic path increases as the length of the path is increased. It decreases as the cross-sectional area is increased. This is analogous to the variation of resistance in electrical circuits, with changes of dimensions.

(4) *Variations of reluctance expressed as an equation.* The various things which determine the reluctance of a magnetic path may be expressed as an equation, thus:

Reluctance (in rels)

= Length of the Magnetic Path (in inches)

× Reluctivity of the Material (as determined from curve in rels per inch cube) divided by Area of Magnetic Path (in square inches)...Equation (21)

(5) *Numerical example.* To determine the reluctance of a certain piece of iron, 20 inches long, and of 4 square inches cross-sectional area, if its reluctivity (as determined from a magnetization curve, for the flux density at which it is to be used) = 0.001.

From equation (21):

$$\text{Reluctance} = \frac{20 \times .001}{4} = 0.005 \text{ rel.}$$

(c) *Reluctance of Non-magnetic Materials.* Since the reluctance of non-magnetic substances neither varies with flux density, nor with the kind of non-magnetic material, it is possible to represent the reluctance of a unit length and unit cross-section of such a substance by a constant number. This number will simply be the ratio of the ampere-turns per inch of length to the flux density in lines of force per square inch. This follows directly from equation (14) and is another way of stating Ohm's Law of the Magnetic Circuit. The reluctivity will be the same no

matter what the flux density. For the units given above, it will equal 0.313. However, it is sometimes customary to express the reluctivity of iron in terms of that of air. When this is done, the air is said to have a "relative" reluctivity of 1. The value 0.313 refers to the absolute reluctivity.

(1) *Variation with dimensions.* The reluctance of a path of a non-magnetic material increases with increased length and decreases with decreased cross-sectional area, in the same manner as for magnetic materials. However, it is sometimes rather difficult to accurately determine just what is the cross-sectional area of the non-magnetic material perpendicular to the lines of force. Thus, for example, the pole of a generator may have a cross-sectional area of 60 square inches. This can be accurately measured. However, the lines of force will spread out in the air-gap under the pole, and hence the cross-sectional area of the air path is greater than 60 square inches. In calculating the reluctance in such a case, it is usual to assume that the paths of the fringing flux at the edges of the poles are straight lines which extend longitudinally to the edge of the armature surface and laterally for a distance equal to the air-gap on each side. The average width is then determined and multiplied by the average axial length, in order to find the approximate cross-sectional area. Of course, in the actual design of such a non-magnetic path, a number of other assumptions must be made, and moreover it is necessary to use available data from tests on similar machines, together with judgment obtained from practical experience along these lines. It thus follows, that absolutely accurate results

are impossible from calculations of this kind, but nevertheless close approximations may be made by experienced designers.

(2) *Variations of reluctance expressed as an equation.* The equation given for magnetic materials (equation (21)) also holds for air and other non-magnetic materials. Since, in this case, the reluctivity can be expressed by a constant number 0.313, that equation may be simplified, for non-magnetic materials, as follows:

Reluctance (in rels)

= Length of the Magnetic Path (in inches)

× 0.313 divided by Approximated Cross-sectional
Area of Magnetic Path (in square inches) Equa-
tion (22)

(3) *Numerical example.* To calculate the approximate reluctance of the air-gap shown in Fig. 13:

The average length of the magnetic path is 1 inch. The cross-sectional area of the face of the pole is $10'' \times 9'' = 90$ square inches. However, the area of the air-gap is greater than 90 square inches and must be found by the method outlined above. The fringe flux extends longitudinally to the edge of the armature surface, which is 12 inches in length. Hence the average axial length of the air-gap = $\frac{1}{2} (10 +$

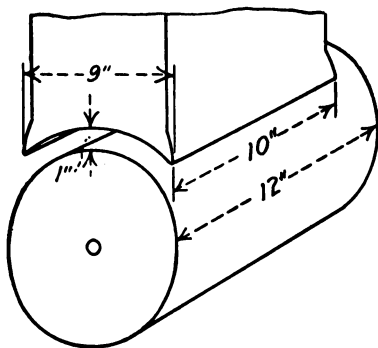


FIG. 13.—Magnetic circuit illustrating a method of calculating the reluctance of an air-gap.

12) = 11. In like manner it is assumed that the fringe flux extends laterally for a distance equal to the air-gap on each side. Hence the average width of the air-gap = $\frac{1}{2}(9 + 11) = 10$ inches. Therefore, the average area equals average width times average length = $10" \times 11" = 110$ square inches.

Hence from equation (22):

$$\text{Reluctance} = \frac{1 \times 0.313}{110} = 0.00284 \text{ rel.}$$

(d) *Effects of Changing Magnetism:*

(1) *Hysteresis.* Although there is no appreciable opposition offered to a change in the direction of magnetism, in a non-magnetic substance, there is a distinct energy loss whenever there is such a change in a magnetic substance. Such a loss is referred to as a "Hysteresis Loss," and may be measured in watts. The energy which disappears as hysteresis loss reappears as heat, and serves to raise the temperature of the magnetic circuit. Hysteresis may be considered as occurring because of the opposition which the minute particles of the magnetic material offer to being magnetized or to having their magnetization changed. Hysteresis is sometimes called "molecular friction." It should be thoroughly understood, that no energy is necessary to maintain a magnetic field. Of course there will be a heating loss in the exciting winding due to the flow of current through a resistance. However, as soon as the flux varies, either in amount or in direction, there is an interchange of energy between the electrical and the magnetic circuits. This interchange occurs through the inducing of e.m.f.'s in the magnetiz-

ing windings. All the energy which is supplied to the magnetic circuit by the electrical circuit is later returned, with the exception of that lost as a result of hysteresis. This explains why hysteresis is likened to friction. Both are conversions of energy to heat and the energy thus converted cannot be reconverted to its original form.

Hysteresis loss is determined by the rate at which the magnetism is changed, by the flux density of the magnetic material and by the particular material used. The hysteresis loss in cast iron is approximately four times as great as that in wrought iron. In general, the harder a magnetic material, the harder it is to reverse its magnetism and hence the greater the hysteresis loss. This explains why annealing or softening iron will reduce the hysteresis loss.

(2) *Eddy currents.* It so happens that the materials which are classed as magnetic materials are also good or fair electrical conductors. Hence, whenever there is a change in magnetism in these materials, either in amount or in direction, e.m.f.'s are induced, according to Faraday's Law of Magnetic Induction, in the magnetic material itself. These give rise to short-circuited currents which are called Eddy Currents or Foucault currents. In most cases they serve no useful purpose, the electrical energy being converted into heat energy, and the inter-linked magnetic fields acting as a drag, if the material is rotating or moving in a magnetic field. In the lesson on "Generators," it will be shown how the hysteresis and eddy-current losses, which are classed as "Iron Losses" exert an additional drag on the armature of the

generator which must be supplied mechanically by the prime mover. This same drag, due to iron or core losses, exists in the motor, between the armature and the field. In the case of the motor, there is less turning effort available at the shaft, on account of these losses. Eddy currents are sometimes made to serve a useful purpose, that is, to act as a brake, in certain types of electrical measuring instruments. In these instruments, it is usual to have an aluminum disk, which passes between the jaws of permanent magnets, on the same shaft as the meter armature. Eddy currents are induced in the disk and the magnetic field interlinked with these currents exerts a drag or torque through its action upon the field or the permanent magnet. The amount of this drag is directly proportional to the speed. This is just the amount required.

Eddy-current loss is usually reduced by subdividing the iron into thin laminations. These are insulated from each other by varnish, shellac, japan, tissue paper, or sometimes simply by rust. The laminations must be perpendicular to the path of the currents, so that the insulation will break up the eddy currents. Laminations vary in thickness from 0.01 inch up to 0.028 inch. The insulation is seldom greater than 15 per cent of the total cross-section. If the laminations are made too thin, too much space will be taken up by the insulation and the cross-section of the iron will be correspondingly reduced. In addition, the expense of construction will be considerably increased. In certain special types of apparatus, iron wire cores are used instead of laminations. While such construction is not as compact as the use of laminations, it limits the eddy-current loss to an exceed-

ingly small value and so is useful where the changes in magnetism are exceedingly rapid.

The power lost in eddy currents, per pound of laminations, is proportional to the square of the thickness of the laminations, the square of the rate of change of the magnetism, and the square of the flux density.

(e) *Circuit Connections:*

(1) *Series.* The reluctances which form the magnetic paths of certain commercial apparatus are in series. In order to obtain the total reluctance of a number of reluctances in series it is simply necessary to add up the separate reluctances. This is analogous to adding up the separate resistances in an electrical circuit, in order to determine the total resistance of the circuit.

(2) *Parallel.* There are no practical magnetic circuits which are entirely in parallel. In order to find the total reluctance, where several reluctances are in parallel, it is convenient to convert each reluctance to its permeance value (that is divide it into one). By adding the separate permeances, the total permeance is obtained and this can then be changed to total reluctance by dividing it into one. This method is analogous to that used for finding the total resistance of a number of resistances in parallel in the electrical circuit. In that case, the conductances were added to find the total conductance, and this was then changed to total resistance.

(3) *Series-parallel.* In most apparatus, the magnetic circuits are complicated and consist of paths in series and in parallel. While, in general, magnetic paths are designed to have reluctances in series, it is impossible to carry this out in most cases, because of magnetic leakage.

Figure 14 shows the magnetic path of a four-pole dynamo. The path of the flux is shown by a single dotted line and its direction by arrow-heads. It is desired to have the flux take the path through the following reluctances in series: From the north pole, through the air-gap, through the armature core, through the air-gap again, through the south pole, and back through the field frame to the north pole. Such a circuit would constitute a series

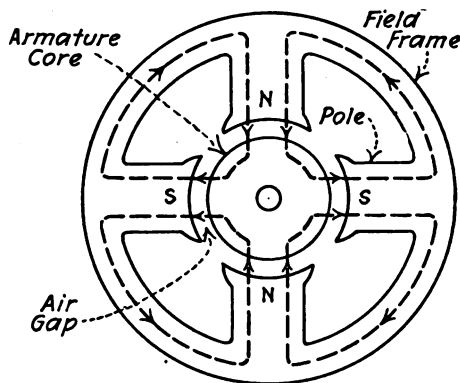


FIG. 14. — The magnetic circuit of a four-pole dynamo.

circuit consisting of three different materials. Of course the air-gap consists of a non-magnetic material and has a much greater reluctance than the others. As a matter of fact, the actual magnetic path is not so simple as this.

There is leakage between the pole tips and hence this leakage flux, which should be less than 25 per cent of the useful flux, is in parallel with that part of the flux which passes through the armature. Hence this is really a series circuit, with parallel branches, or in other words a series-parallel circuit. It can readily be seen that a great deal of practical experience would be required in calculating the reluctance of such a circuit, since certain elements would have to be estimated. If all the reluctances were known, however, the total reluctance could easily be found by adding up the

reluctances in series, and the permeances in parallel, then changing the total permeance to reluctance by dividing it into one and adding this to the sum of those in series

(f) *Circuit Calculations.* In the practical calculation of magnetic circuits, the flux required to obtain a certain induced e.m.f. or to get some other useful effect, is first calculated. The cross-sectional area of each portion of the magnetic circuit is then determined, so that the required flux density will be obtained together with the required mechanical construction. In general the cross-section is made of such size that the flux density of the magnetic material will not pass the point of saturation. Having determined the required flux density in each part of the circuit, the next step is to determine the necessary number of ampere-turns. It is usual to determine the number of ampere-turns necessary for each part of the magnetic circuit separately. These are then totaled and the result gives the total m.m.f. or ampere-turns, necessary to force the required flux through the entire circuit. By thus calculating the various parts separately, it is easier to take into account the fact that a part of the circuit is of a magnetic material and part of a non-magnetic material, also that the different magnetic materials have different reluctivities. The following numerical example will illustrate the general procedure in the calculation of simple magnetic circuits:

Numerical example. To find the ampere-turns necessary to develop a useful flux of 200,000 lines through the armature in Fig. 15. (Assume a leakage factor of 1.1.)

Assuming a leakage factor of 1.1, this means that the leakage flux between the pole tips and pole sides equals

10 per cent of the useful flux. Hence, in order to have 200,000 lines of force pass through the armature, 220,000 will have to pass through the pole pieces and yoke. The various parts are calculated separately, as explained above:

Yoke. Cross-sectional area = $4'' \times 1'' = 4$ square inches. Hence the flux density, in lines per square inch = $220,000/4 = 55,000$. The ampere-turns per inch of length of the

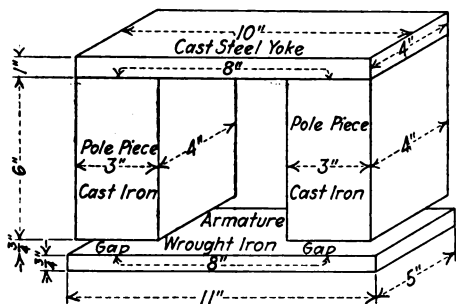


FIG. 15. — A typical magnetic circuit problem.

magnetic path, in the cast steel, can then be determined from the curve (Fig. 2). The ampere-turns per inch thus determined equal 20. Since the magnetic path through the cast steel is 8 inches

long, the ampere-turns necessary to send 220,000 lines of force through this part = $8 \times 20 = 160$.

Pole pieces. Cross-sectional area = $3'' \times 4'' = 12$ square inches. Hence, the flux density, in lines per square inch, equals $220,000/12 = 18,333 +$. From the curve for cast iron, Fig. 2, the ampere-turns per inch necessary to maintain this flux density = 34. Therefore, since each pole piece has a magnetic path = 6 inches, the total path through the cast iron is 12 inches, and the ampere-turns necessary will be $12 \times 34 = 408$.

Air-gap. Since air is a non-magnetic material, the necessary ampere-turns can be calculated by means of Ohm's Law of the Magnetic Circuit. However, it is first necessary to find the reluctance. Due to the fringe flux at the pole

tips, the cross-sectional area of the air-gap will be greater than 12 square inches (the area of the pole face). On the 4 inch side of the pole, the armature overlaps a half inch at each end. Hence, the average depth of the air-gap in this direction $= \frac{1}{2} (4 + 5) = 4\frac{1}{2}$ inches. Assume that the flux extends for a distance equal to the length of the air-gap in entering the armature on the 3 inch side. Then the average width of the air-gap equals $\frac{1}{2}(3 + 4\frac{1}{2}) = 3\frac{3}{4}$ inches. Therefore the average cross-sectional area of the air-gap $= 4\frac{1}{2} \times 3\frac{3}{4} = 16.87$ square inches. Then, from equation (22), the reluctance of the air-gap $= \frac{\frac{3}{4} \times 0.313}{16.87} = 0.0139$

rel. Then, from Ohm's Law of the Magnetic Circuit, (equation (13)), the magnetomotive force required to send 200,000 lines through each air-gap $= 200,000 \times .0139 = 2780$. Since there are two air-gaps, in this case, the total flux required by the air-gaps will equal $2 \times 2780 = 5560$ ampere-turns.

Armature. Cross-sectional area $= 5'' \times \frac{3}{4}'' = 3\frac{3}{4}$ square inches. Hence the flux density $= 200,000 / 3\frac{3}{4} = 53,300$ lines per square inch. From the curve for wrought iron, Fig 2, it is found that for this flux density, 9.5 ampere-turns per inch of length are necessary. Since the magnetic path is 8 inches long, $8 \times 9.5 = 76$ ampere-turns are required by the armature.

Hence, adding these various magnetomotive forces which have been determined for each part separately, the total ampere-turns required will be found. Thus, $160 + 408 + 5560 + 76 = 6204$ ampere-turns necessary to develop a useful flux of 200,000 lines in the magnetic circuit.

The above calculations may be tabulated, as follows:

Name of Part	Area in Sq. Inches	Flux Dens. in lines per sq. in.	Ampere- turns per in. length (from curve)	Length of Mag Ct. inches	Ampere- Turns neces- sary
Yoke..... (Cast Steel)	4	55000	20	8	160
Pole Pieces..... (Cast Iron)	12	18333	34	12	408
Air-Gap.....	16.87	11860		1.5	5560
Armature (Wrought Iron).	3.75	53300	9.5	8	76
Total.....					6204

In order to be on the safe side, it is usual to increase the total calculated ampere-turns by about 10 per cent, in order to take care of reluctances of joints, and inaccuracies of assumptions and of magnetic curves and data. An inspection of the ampere-turns required by each part, in the above problem, shows that the air-gap requires very much more magnetomotive force than any of the other parts. This suggests a short-cut for the calculation of similar circuits, since if the ampere-turns required by the air-gap are calculated, and this number is increased by 20 per cent, the result will be close enough. However, it should be remembered that such a calculation is only approximate and only applies where the magnetomotive force required for the air-gap is large as compared to that required for the other parts of the magnetic circuit.

Outline of Lesson 4 — ELECTRICAL INSTRUMENTS

1. VOLTMETERS AND AMMETERS:

- (a) Differences between voltmeter and ammeter.
- (b) Types:
 - (1) Moving coil and stationary permanent magnet.
 - (2) Stationary coil and moving iron.
 - (3) Moving coil and stationary coil.
 - (4) Hot-wire type.
 - (5) Other types.
- (c) Method of connection:
 - (1) Voltmeters.
 - (2) Ammeters.
- (d) Care and precautions.

2. WATTMETERS:

- (a) Principles and Use.
- (b) Dynamometer-type wattmeter:
 - (1) Description.
 - (2) Method of calibration.
 - (3) Method of connection.
 - (4) Correction for power consumed in instrument itself.
 - (5) Compensation.

3. WATT-HOUR METERS:

- (a) Use.
- (b) Types:
 - (1) Commutator type.
 - (2) No-commutator type.

4. AMPERE-HOUR METERS:

- (a) Use.
- (b) Description.
- (c) Connection in circuit.

LESSON 4 — ELECTRICAL INSTRUMENTS

1. Voltmeters and Ammeters

(a) *Differences between voltmeter and ammeter.* Since the current flowing in any circuit is always proportional to the e.m.f. (in accordance with Ohm's Law), practically every manifestation of electricity which is used to measure current can also be used to measure voltage. In other words, an ammeter can be used as a voltmeter, with several minor alterations. Since the ammeter carries load current, or a definite proportion of load current; its resistance must be low. On the other hand, since the voltmeter must stand the line voltage, its resistance must be high so that little current will flow through it and hence so that the energy loss will be small. Hence, the difference between the two classes of instruments lies in the degree of sensitiveness. Each class of instrument requires a certain amount of current to flow through it in order for it to indicate. The voltmeter is very sensitive and will indicate an extremely small current flow. The ammeter which carries only a small proportion of the load current is also very sensitive. However, where the ammeter carries the full-load current, its windings are larger, and an appreciable current is necessary in order to make it indicate. The amount of current which flows through a voltmeter is limited and controlled not only by the size of the windings, but also by a resistance in series called a "multiplier." The amount of current flowing through an ammeter is determined by the resist-

ance of the ammeter windings, but in cases where only a certain proportion of the load current flows through the ammeter, it is also determined by the value of the resistance, called an "ammeter shunt," placed in parallel with the ammeter. The resistance of this shunt is made low, in order that most of the current will pass through it, instead of through the instrument. Both voltmeters and ammeters must be properly calibrated in order to give correct readings.

(b) *Types:*

(1) *Moving coil and stationary permanent magnet.* This is the "galvanometer" type of instrument. It is a development of the D'Arsonval galvanometer, and depends for its indication upon the motor action existing between the permanent magnetic field and the current-carrying coil mounted in this field. According to Maxwell's Law of Motor Action, when current is passed through the coil, it tends to change its position so as to embrace the maximum number of lines of force in a positive direction. The D'Arsonval galvanometer operates on this principle also, but merely indicates the presence and approximate degree of the current or voltage, whereas the ammeter or voltmeter indicates the exact amperage or voltage, as the case may be. The permanent magnets in this type of instrument are made of steel. They are of the horseshoe type, and are shaped as shown in Fig. 16. The poles of the magnet are fitted with soft-iron pole pieces, so shaped as to give a uniform magnetic field. A stationary soft-iron core is placed between the poles, thus leaving an annular air-gap for the moving coil. The effect of this construction is that the coil will cut the same number of lines of force, no matter what its position may

be. Hence the deflections will be exactly proportional to the current flowing in the coil and the instrument may be calibrated with uniform scale divisions. The coil of wire is rectangular in shape and is extremely light. It is pivoted on sharp points which rest in jeweled bearings. There is a narrow spiral hair spring at the top and the bottom of the coil. These springs serve to restrain the motion of the coil, and also to lead the current in and out.

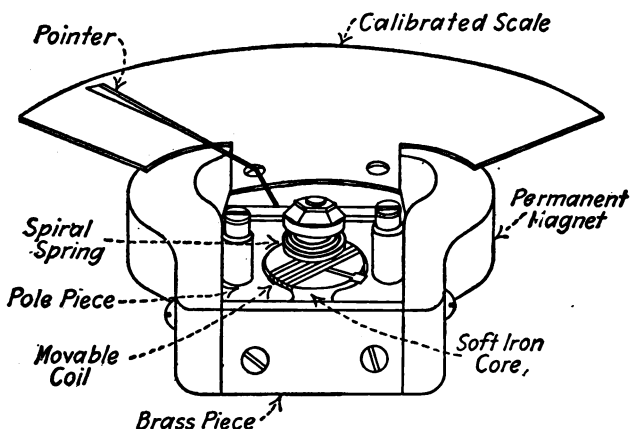


FIG. 16. — Permanent magnet moving coil instrument.

A thin aluminum pointer is attached to the movable coil and serves to indicate the readings. The springs bring the pointer back to zero when there is no current flowing in the coil. The coil is wound on a light copper or aluminum frame. This acts as a support for the coil, and also serves to make the instrument "dead beat." (Dead-beat instruments come to rest quickly, registering the reading with no vibration.) The supporting frame accomplishes this, due to the eddy currents which are

induced in it. The fields of these induced currents react on the field of the permanent magnet, and according to Lenz's Law tend to oppose further motion. Hence the eddy currents provide a braking action.

A brass piece extends between the poles and the soft-iron core is fastened to this. A calibrated scale is provided under the end of the pointer, and in the portable instruments a mirror is placed just below the scale. The proper way to read the instrument is to look down at the pointer in such a way that its image cannot be seen in the mirror. This guards against errors resulting from readings made at an angle.

In addition to the portable instruments, larger instruments of the same type are made for switchboard work. Instruments of the galvanometer type are among the most accurate. They can be used for direct current only. In order to obtain a deflection in the proper direction, the positive side of the line must always be connected to the terminal of the instrument marked plus (+). If instruments of this type are connected to an alternating-current circuit the needle will not be deflected, but will merely vibrate. It receives an impulse to move in one direction, but before this can be effected, it receives an impulse in the reverse direction due to the rapid reversal of the current. As a result, no deflection can be obtained. Instruments of this type are liable to be affected by stray magnetic fields, and these should be guarded against.

The usual resistance of the movable coil of the voltmeter is approximately 60 ohms. The instruments are so designed that 0.6 volt will produce a full-scale deflection. Hence, from Ohm's Law, the current flowing in

the coil, for a full-scale deflection will be about 0.01 ampere. In a voltmeter designed for a full-scale deflection at 150 volts, a multiplier is connected within the instrument of such resistance that the difference of potential across the coil will be cut down to 0.6 volt. Hence, when a current of 0.01 ampere flows, the resistance of the multiplier, in series with the coil, must cause a voltage drop of $150 - 0.6 = 149.4$. It follows, from Ohm's Law, that this resistance must equal 14,940 ohms. (Resistance = $149.4 / 0.01 = 14,940$ ohms.) Hence, the total resistance of the multiplier and coil will equal 15,000 ohms. It can be seen that there is a total resistance of 100 ohms per scale division. Portable voltmeters are very often provided with two scales, one for reading high voltages, and the other for low readings. It is obvious, that if a full-scale deflection is desired at a lower voltage, a lower resistance multiplier will be necessary in series with the movable coil. Hence, in this case, a third terminal must be provided with connection made within the instrument so that only the necessary resistance is in series.

The usual resistance of the movable coil, together with the connecting leads, in the ammeter is approximately 1 ohm. In these instruments, about 0.045 volt will produce a full-scale deflection. In other words, a current of 0.045 ampere flowing in the coil will produce a full-scale deflection. Hence, in the galvanometer type of instrument, the ammeter is more sensitive than the voltmeter, although its windings have lower resistance. In order to measure different ranges of current, shunts of varying resistance are furnished with the ammeters. Thus, if it is desired to measure a current of 50 amperes, the shunt

resistance (for a full-scale deflection) would be obtained as follows: Since a current of 0.045 ampere is required by the coil for a full-scale deflection, the rest of the current, $50 - .045 = 49.955$ amperes must flow through the shunt. But since the resistance of the movable coil and leads equals 1 ohm, a potential difference of 0.045 volt will send the .045 ampere through the coil. Since the coil and the shunt are in parallel, there must also be a potential difference of 0.045 volt across the shunt. Hence, the resistance of the shunt must equal $.045/49.955$ (from Ohm's Law) = $0.0009 +$ ohm. It can be seen that in this case, since the current through the shunt must be about 1100 times as much as that through the coil, the resistance of the shunt must be $1/1100$ th that of the coil. In some of the smaller ammeters, the shunt is contained within the case of the instrument, but for currents larger than 25 amperes separate shunts are provided. These shunts are usually made of an alloy of copper, nickel and ferromanganese, called "Manganin." Several strips are sweated into heavy brass blocks, and separate terminals are provided for line connection and for instrument leads. The line terminals are much larger than the instrument terminals. The ammeters having external shunts are calibrated in amperes, and can be used with a number of shunts. Thus, if an instrument is calibrated so that a full-scale deflection reads 100 amperes, it can be read directly when a 100-ampere shunt is used. It should never be used with a shunt marked more than 100 amperes. If it is used with a 50-ampere shunt, then 50 amperes will produce a full-scale deflection, and hence in order to get the true amperage, the reading must be

divided by two. When used with a 25-ampere shunt, 25 amperes will produce a full-scale deflection, and hence the reading of the ammeter must be divided by four. Most instruments have several scales, and in this case the scale is read which corresponds to the shunt being used.

(2) *Stationary coil and moving iron.* These are the "Iron Vane," and "Plunger" type of instruments. Although these instruments have been developed mainly for alternating-current work, they can be used on direct current also (when calibrated for direct current) and they are used extensively, because of their simplicity and cheapness, where great accuracy is not a requirement. The principle of operation of these instruments is the attraction which a current-carrying coil or solenoid exerts upon soft iron. This attraction does not depend upon the direction of the current, and hence this explains why the instruments can be used for either direct-current or alternating-current circuits. In instruments of this type, the only difference between voltmeters and ammeters, aside from calibration, is that the voltmeters have the stationary coil wound with a great many turns of fine wire and have multipliers in series for changing the range, whereas ammeters have a stationary coil which consists of a few turns of heavy wire. Shunts are not used with ammeters of this type, as it is a comparatively simple matter to pass the entire current to be measured through the stationary coil. Although the same principle is the basis of all instruments having a stationary coil and moving iron, there are a number of variations in the method of construction. Some of these are:

The Iron Vane instruments. A small soft iron vane or

segment is attached to a pivoted shaft, set within the current-carrying solenoid. In one method of construction, the segment or vane is normally held off center by the action of springs. When current flows through the solenoid, the vane moves nearer to the center, where the stronger field exists, and in so doing, it turns the shaft and hence the attached aluminum pointer. In the "inclined coil" instruments, the coil is inclined at an angle of about 45 degrees to the shaft. The iron vane is mounted on the shaft, at an angle, and its normal position, as determined by the action of springs, is such that it is cut by few lines of force. As soon as current passes through the solenoid, the vane tends to swing into such a position that it will be in line with the magnetic field. In other words, it tends to take the position which will allow the largest number of lines of force to pass through it and this is the position in which it is parallel to the lines of force within the coil. The vane in turning, turns the shaft and pointer, and is resisted by the action of the springs. Damping is effected by an aluminum vane, which turns with the iron vane. The resistance of the air to the movement of the aluminum vane makes the instrument practically dead-beat, the final indication being obtained without vibration.

Plunger types. In these instruments, a soft-iron plunger is drawn into a solenoid, either against the action of gravity, using a counterweight, or against the action of springs. Damping is obtained through the inducing of eddy currents in the plunger. Although these instruments are simple, they can only be used for rough work and ordinary commercial measurements, in which

instruments of the stationary coil and moving iron type are required, are usually performed with iron vane type.

Iron bar type. In this type, a stationary and a movable iron bar are placed within the solenoid, and in such a position that when current passes through the solenoid, the ends of the rods receive like magnetization and hence repel each other. The movable rod is pivoted on the shaft at the center of the coil and moves away from the stationary rod, thus turning the shaft and moving attached pointer over a calibrated scale. The movement is resisted by a counterweight. A modification of this construction is used in instruments which have a stationary and movable soft-iron circular segment. The ends of the segments become magnetized in the same way as the rods (like polarity together), and hence the movable segment is repelled from the stationary one. This turns the shaft, to which the segment is attached, thus moving the pointer over the scale. Springs control the motion, thus giving more positive action than gravity control. Damping is obtained by the use of aluminum vanes attached to the movable element.

In all instruments of the "stationary coil and moving-iron" type, the magnetic pull is nearly proportional to the square of the current in the coil. Hence, if the current is doubled, the pull on the soft iron will be increased four times. On this account, the scale divisions for large values of current or of voltage must be farther apart than for the lower values. This results in a crowding of the divisions at the lower end of the scale. As these instruments are mostly used for switchboard work, an irregular scale is not a serious disadvantage.

(3) *Moving coil and stationary coil.* These instruments are of the "Dynamometer" type. They can be used for either direct current or alternating current. The moving coil and the stationary coil are connected in series, and the current flows through them in such a direction that they attract each other. This is in accordance with the law of magnetic action between parallel, current-carrying conductors. Although the dynamometer principle can be applied to the measurement of both voltage and amperage, commercial instruments of this class are in general limited to voltmeters. This is because it is difficult to lead heavy currents in and out of the movable coil, and moreover it is difficult to construct that coil of sufficient capacity to carry very much current. The use of a shunt is impracticable in instruments of the dynamometer type. The force tending to turn the coil is proportional to the square of the current, and hence an irregular scale is necessary in these instruments. Voltmeters of the dynamometer type have the coils made of high resistance, and also have a multiplier connected in series. They are particularly adapted to alternating-current work, and are not much used in commercial direct-current work. These instruments, since they depend upon electromagnetism for their indication, are affected by stray fields. Where used for direct-current work, the instrument will be affected by terrestrial magnetism, unless special precautions are taken to eliminate its effect. The effect of terrestrial magnetism will be nil, if two readings are taken (one with the current reversed), and their average taken as the true reading. With the exception of wattmeters, instruments of the dynamometer type are chiefly used for standardization and laboratory work.

(4) *Hot-wire type.* These instruments depend for their indication upon the heating effect of electricity. They are of comparatively simple construction, are cheap, and can be used for either alternating current or direct current. Since the action of hot-wire instruments does not depend upon magnetic effects, these instruments are not affected by stray fields. They can be used for either voltmeters or ammeters, but the hot-wire ammeter is used to a greater extent than the voltmeter. Where currents larger than 5 amperes are to be measured, shunts are provided with the ammeter. The current to be measured, or a certain definite proportion of it, passes through a wire of platinum-silver, or other non-oxidizable metal of high resistance and low temperature coefficient. The expansion of the wire, when heated, causes a sag, and this motion is transmitted by means of suitable pulleys, to a pointer moving over a calibrated scale. Although the same principle forms the basis of all hot-wire instruments, the method of construction differs in various makes. As these instruments are not used to any extent for commercial direct-current work, the actual construction will not be taken up in this book. Since the heat energy is proportional to the square of the current, the scale of hot-wire instruments is irregular, as in the case of "Iron Vane," and "Dynamometer" types.

(5) *Other types.* Induction instruments will not be described in this book, since they can only be used for alternating current. Electrostatic voltmeters are only used for high-voltage work. They depend for their action upon the attraction between opposite charges of "static" electricity. These instruments can be used for either

direct current or alternating current. However, ammeters cannot be constructed on this principle.

(c) *Method of connection:*

(1) *Voltmeters.* Voltmeters may be connected between

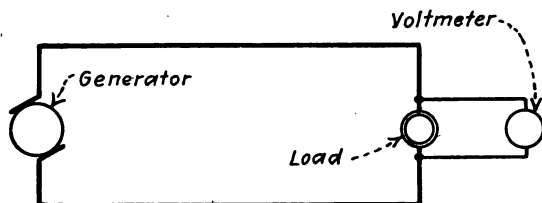


FIG. 17. — Correct method of connecting a voltmeter.

any two points, whose difference of potential it is desired to measure. (See Fig. 17.)

(2) *Ammeters.* Ammeters must be connected in series with the load and the line. (Fig. 18.) If connected in parallel with the load, the ammeter will receive full-line

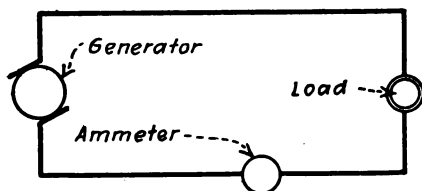


FIG. 18. — Correct method of connecting an ammeter.

voltage and will probably be burned out.

(d) *Care and precautions.* These instruments should be handled as carefully as

a fine watch. When a portable meter must be

used in any particular position, the pointer should stand at zero, when there is no current in the instrument. If it is not at zero, it can be adjusted to this position in most makes, by the shifting of the spring post plate, using a small screw driver. In general, portable instruments give the best results, when used in a horizontal position,

although they can usually be used in any position, provided the proper adjustment is made. When using voltmeters having two scales, care should be taken not to connect the high-voltage to the low-voltage terminal. If this is done, the needle will be bent, or possibly the instrument will be burnt out. Ammeters which are made for use with external shunts are usually so marked, and should never be used without them. If such an instrument is used without a shunt, it will be burnt out. Care should be taken to use the shunts and leads which come with the instrument. Ammeters which can be used without shunts can usually be distinguished by their binding posts, which are made large, in order to carry the heavier currents. Ammeters should always be connected as indicated under (c) (2).

2. Wattmeters

(a) *Principles and Use.* Instruments for the measurement of electrical power are called "indicating wattmeters," or simply "wattmeters." According to equation (4), electrical power (in direct-current work) measured in watts is equal to the product of voltage times amperage. Hence an instrument for indicating the power being consumed in a circuit must have a voltage and a current element. For direct current work, the only principle of operation available is that of the dynamometer (stationary coil and moving coil). The dynamometer type of wattmeter can also be used for alternating current, in addition to the induction wattmeters, which only operate on alternating current.

(b) *Dynamometer type wattmeter:*

(1) *Description.* The wattmeter is similar in construction to the instruments of the permanent magnet-moving

coil types, with the exception that the stationary coils are used instead of the permanent magnet. The stationary coil is in two parts with the movable coil between. The stationary coils are of low resistance and carry load current. The movable coil is of high resistance, has a high resistance winding in series with it, and the small amount of current flowing through it is proportional to the impressed voltage, since it is connected in parallel with the load. Hence the deflections are proportional to the product of the load current times the impressed voltage, or in other words, to the power expended. The instrument scale is calibrated directly in kilowatts (sometimes in watts). By pressing a small button located beneath the scale, the potential circuit can be closed. This guards against overheating of the movable coil and the multiplier when the instrument is not being read.

(2) *Method of calibration.* These instruments are calibrated by means of standard ammeters and voltmeters, and the same calibration holds good for both direct current and alternating current.

(3) *Method of connection.* The large terminals on the instrument lead to the stationary coils, and should be connected in series with the line and the load; the small terminals, which lead to the movable coil, are usually connected in parallel with the load. (Fig. 19.)

(4) *Correction for power consumed in instrument itself.* The instrument will read too high, if not compensated, since the current flowing through the stationary coils is not only that being drawn by the load, but is also that drawn by the movable coil. In order to correct for this error, the power consumed by the movable coil must be

subtracted from each reading. This excess power may be calculated from equation (6) as follows:

$$\frac{\text{Voltage}^2 \text{ (across load — in volts)}}{\text{Resistance (of movable coil — in ohms)}} = \text{Excess Power (in watts).}$$

If the potential leads are connected on the line side of the instrument, instead of on the load side, it is obvious that the voltage across the instrument will be greater

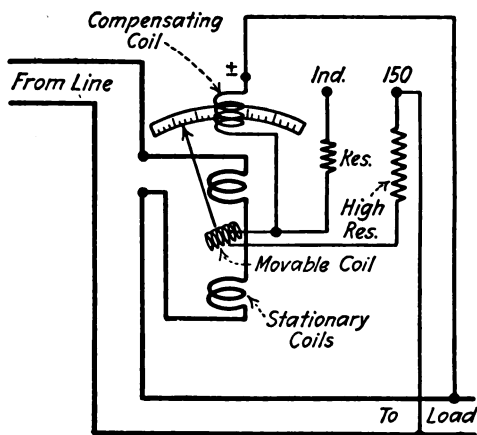


FIG. 19. — Connections of dynamometer type wattmeter.

than that across the load, by the amount of drop caused by the stationary coils. The excess power correction, in this case, will equal the product of the current flowing through the stationary coils squared times the resistance of the stationary coils.

(5) *Compensation.* In most commercial wattmeters, no correction for power consumed in the instrument itself is necessary, since a special compensating coil is put in the instrument for this purpose. This compensating coil

is connected in series with the movable coil, and is wound in such a direction that its field opposes the field of the stationary coils. Since this compensating coil is in series with the movable coil, it weakens the field of the stationary coils by an amount proportional to the current in the movable coil. If the circuit is traced through, it will be seen that at no load, the movable coil, the compensating coil, and the stationary coils, are in series, the same small current flowing through all. At no load, the compensating coil is adjusted so that its field is equal¹ and opposite to the field of the stationary coils. Hence, the pointer remains at zero at no load, in spite of the current flowing in the windings of the instrument. This compensation is correct for all loads, since the current in the compensating winding is fixed in amount, and is always equal to the no-load current of the stationary coils. A third terminal is usually provided, marked "Ind" (Independent) which leaves the compensating coil out of the circuit, and which is connected to the movable coil, through a resistance equal in amount to that of the compensating coil. In ordinary commercial direct-current work the compensating coil is usually left in the circuit, the independent terminal being only used for special work.

3. Watt-hour Meters

(a) *Use.* These meters are used to determine the amount of electrical energy being expended. They actually measure and add up the work done during each hour, or fraction thereof, that the current flows. Since the energy expended depends upon the watts consumed and the time of use, the energy meter is calibrated in kilowatt-hours.

(b) *Types.* The "Motor" type of watt-hour meter is the only one available for the determination of amount of electrical energy expended. In instruments of this type, a small motor is made to rotate at a speed directly proportional to the energy being expended. For direct-current work, watt-hour meters are subdivided into two classes:

(1) *Commutator type*¹, Fig. 20: These meters operate on the dynamometer principle. They contain a stationary coil and a movable coil. The movable coil is arranged to rotate continuously, in one direction, by means of the commutator, which reverses the current in each subdivision

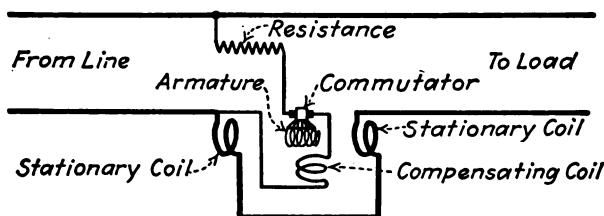


FIG. 20. — Internal connections of commutator type watt-hour meter.

of the movable coil, or armature, as the subdivision comes under the influence of a pole of different polarity. The movable coil is subdivided into a number of symmetrically spaced coils, in order to obtain a smooth and continuous impulse. This arrangement is exactly the same as in any other direct-current motor, with the exception that there is no iron in the stationary (field) coils, nor in the armature. The stationary coils or fields are connected in series with the line and the load; the armature is connected in parallel with the load, additional resistance being placed in series with it. Hence, the pull exerted between the field and the

¹ NOTE: Before studying this paragraph, it is desirable to study paragraphs 2, 5, 6, 7, and 9 under lesson on "The Direct-Current Motor."

armature is proportional to the product of the impressed voltage times the load current. The speed of the armature shaft is recorded on dials, by means of a worm attached to the shaft engaging with a train of wheels.

Because of the absence of iron in the magnetic circuit, the field is comparatively weak, and hence the counter e.m.f. induced in the rotating winding is practically negligible. Hence, as the load is increased, there will be more current through the field coils and an increase of field strength. Since the counter e.m.f. is negligible, there will be no decrease in armature current. Therefore, the net result of increased load will be increased speed. (The term "load," as used here, refers to the electrical load, whose energy consumption is being measured.)

A motor of this type would run away, since it has no mechanical load attached. For this reason, an eddy-current brake is used so that the speed will always be proportional to the energy expended. As the speed decreases, the braking action decreases also. In other words, the retarding force is exactly proportional to the speed. The eddy-current brake consists of a copper or aluminum disc, mounted on the vertical armature shaft in such a manner that it rotates between the poles of two permanent magnets. According to Faraday's Law of Electromagnetic Induction, the metal disc has e.m.f.'s induced in it, when it cuts the fields of the permanent magnets. These induced e.m.f.'s set up eddy currents in the disc, and according to Lenz's Law, the fields due to these eddy currents react with the fields of the permanent magnet in such a way as to tend to prevent further rotation of the disc. The greater the speed of the disc, the higher will

be the induced e.m.f.'s, and consequently the eddy currents will be greater in amount, and the magnetic drag will be correspondingly increased. The speed of the armature will attain a constant value when the torque developed is equal and opposite to the counter-torque of the eddy-current brake (neglecting friction). It has been shown above that the torque developed will always be proportional to the product of impressed voltage times load current. Also that the counter-torque is always proportional to the speed. Hence, since the torque equals the counter-torque whenever speed is constant, the speed will always be proportional to the product of impressed voltage times load current (or in other words to the watts being consumed at that particular time). It follows that in such a motor, there will be a definite speed corresponding to every value of the energy being expended. If the energy is doubled, the speed will be doubled, etc.

Although friction is reduced to the smallest possible amount by the use of jeweled bearings and light moving parts, still there is always a certain energy loss due to it, which must be compensated for. The way in which this is usually done is to put a small coil in series with the armature, and in such a position that its field will aid the field of the main field coils. The position of the coil can be adjusted so that its distance from the armature can be varied. It should be placed far enough from the armature to prevent rotation at no load, but near enough to start the armature rotating when the smallest current flows through the coils of the instrument. When placed in this position, the extra torque supplied by the

compensating coil is just sufficient to overcome the friction.

The speed of the meter may be adjusted by moving the two permanent magnets either closer to, or further away, from the center of the metal disc. The further in towards the center the magnets are moved, the less will be the eddy currents induced and hence the greater will be the speed. It is usual to have the magnets adjusted so that the dials can be read directly. The number on the rotating disc is the constant of the meter, and signifies the number of watt-hours registered for each revolution of the disc.

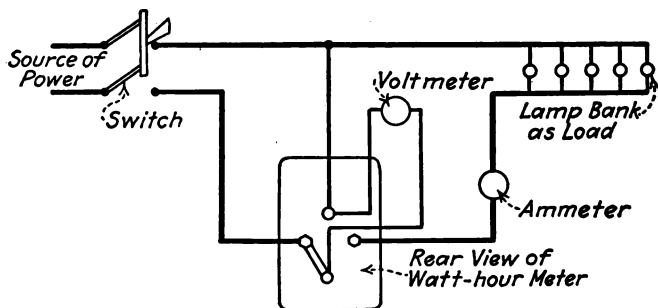


FIG. 20 (a). — External connections of a commutator type watt-hour meter. A voltmeter and ammeter are shown connected in the circuit for calibrating the watt-hour meter.

Thus if the meter constant is 0.4, then 0.4 watt-hours are recorded on the dials for each revolution of the disc. The method of connecting a watt-hour meter in an external circuit is shown in Fig. 20 (a).

(2) *No-commutator type*. Meters of this type are essentially motors whose armatures always cut the same direction flux. (Homopolar motors.) The chief advantages of this type are absence of commutator and use of light moving parts. The principle of operation is the law of motor action which states that a conductor, free to move,

and carrying a current whose direction of flow is at right angles to a fixed magnetic field, will be moved out of this field, and in a direction at right angles both to the direction of current flow and to the field. Figure 21 further illustrates the action of meters of this type. Current is led into the metal disc by means of the mercury in which it floats. The current direction is at right angles to the field of the electromagnet. The circular steel ring above the magnet serves to complete the magnetic path,

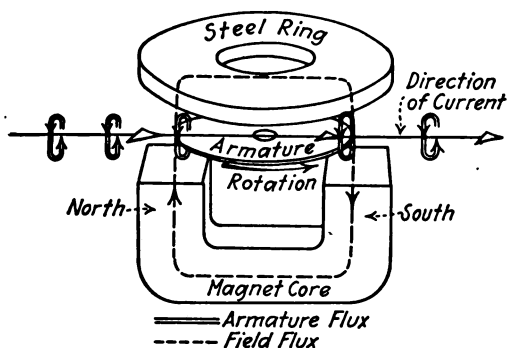
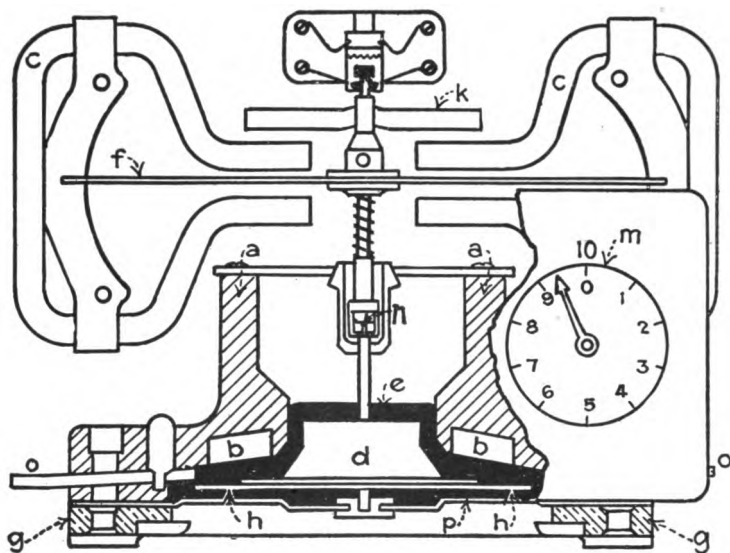


FIG. 21.— Diagram illustrating the principle of the no-commutator watt-hour meter.

and the arrangement is such that the metal disc is free to revolve in the gap. With the direction of flux and of current as shown by the arrows, it can be seen that at the left the magnetic force acts towards the observer, while at the right, it acts away from the observer. Hence, the resulting rotation will be in a counter-clockwise direction (looking down on the disc).

A common type of no-commutator meter (Sangamo) Fig. 22, has a molded insulation receptacle, with thin pressed metal bottom, which is attached by means of a

thick brass clamping ring. The armature is contained in the exceedingly shallow space between the inside of the



INDEX TO LETTERING	
a	Molded Insulation Receptacle
b	Steel Ring-Return Plate
c	Permanent Magnets
d	Non-metallic Float
e	Mercury
f	Aluminum Brake Disc
g	Brass Clamping Ring
h	Copper Armature Disc
k	Heavy Load Adjustment Disc
m	Recording Dial
n	Jewel Bearing
o	Current Terminals
p	Pressed Metal Bottom

FIG. 22. — Cross-section of upper part of Sangamo watt-hour meter.

receptacle and the metal bottom. This armature, which floats in mercury, is made of a thin copper disc. The

mercury is above the disc, as well as below. The necessary buoyancy for lifting the armature, shaft and other moving parts, is obtained through the agency of a solid non-metallic float, riveted to the copper disc. A jeweled bearing is located at the top, and there is a small amount of pressure against this. This method of construction guards the meter against shocks and at the same time reduces the friction to a very low value. The meter has an inverted pocket above the armature, which prevents the mercury from being spilled out, no matter what the position of the instrument. The armature carries load current, or a definite proportion of it, and nickel-plated current terminals are located at each side of the molded insulation receptacle. These are imbedded in the insulation, touching the mercury within the receptacle, thus leading the current to and from the copper disc. A laminated "U" shaped iron yoke is bolted to the brass clamping ring at the bottom of the receptacle. This forms the magnet core for the shunt coil. This coil is of very fine wire and is connected across the line, so that the magnetization will be proportional to the impressed voltage. A soft iron ring is located just above the copper disc, or armature, and serves to complete the magnetic circuit, the armature rotating in the gap between the ring and the magnet core. Since the magnetic field is proportional to impressed voltage, and load current flows through the armature, the armature is continuously impelled at right angles to the field, and the torque developed will be proportional to the energy being expended. The same method as in commutator meters is used to get the speed proportional to the torque. An aluminum disc,

mounted on the same shaft as the armature, is made to pass between the poles of two permanent magnets. The eddy currents induced provide a mechanical load, or counter-torque, and this counter-torque is directly proportional to the speed. Since torque must balance counter-torque, for every constant value of speed, the torque will also be proportional to the speed, and hence the energy being measured will be proportional to the speed.

In Sangamo meters used for over 10-ampere service, shunts are supplied, the meter being designed to carry 10 amperes as in the case of instruments for use without shunts.

The registering mechanism is similar to that used in commutator-type instruments. It consists of gearing, operated by the rotating shaft and properly connected to the recording dials.

The heavy load adjustment is obtained by raising or lowering a soft iron disc located just above the permanent magnets. This varies the strength of the magnetic field through which the aluminum disc passes, thus adjusting the speed of the meter without moving the magnets.

Light load compensation is obtained by means of an adjustable shunted circuit, which passes a small current continuously through the armature even at no load. This provides the torque required to overcome friction. This starting current is obtained by means of a thermo-couple. The thermo-couple consists of two dissimilar metals connected together and in series with the armature. A heating coil of high-resistance wire surrounds these metals. The heating coil is in series with the potential coil. The thermo-couple generates a small e.m.f. which

sends a small compensating current through the armature. Due to the nature of such a device, the current direction will always be the same. Hence care must be taken to connect the instrument in the circuit with the positive terminal to the positive side of the line, as marked, as otherwise the current from the thermo-couple will add its drag to the effect of friction, instead of compensating for friction. By moving, either to the right or to the left a small clamp, set on a pair of parallel wires, in front of the instrument, at the bottom, adjustment of the amount of the compensating current may be made.

Sangamo instruments may be used with alternating current as well as direct current. Instruments for alternating-current use have all parts of the magnetic circuit laminated and also contain a special condenser in series with the shunt coil. The measuring elements are somewhat differently arranged, in that the main current energizes the field, while the potential current passes through the armature. Otherwise, they are practically the same as the instruments used for direct-current circuits.

4. Ampere-hour Meters

(a) *Use.* These instruments are only used in direct-current work and principally in connection with storage batteries. Where the voltage is practically constant, the energy expended will be proportional to the ampere-hours and the actual watt-hours can be obtained by multiplying the ampere-hours by the voltage.

(b) *Description.* These instruments are all of the no-commutator type, and are similar in construction to the watt-hour meters described above, with the exception that a

permanent magnet is used instead of an electromagnet, since a potential element is not required in an ampere-hour meter. The registering mechanism is constructed so that the ampere-hours can be read directly from a single dial.

(c) *Connection in circuit.* Ampere-hour meters are connected in series with the line and the load, in the same manner as ammeters.

Outline of Lesson 5 — DIRECT — CURRENT MEASUREMENTS

1. CURRENT:

- (a) With ammeter.
- (b) With standard resistance and voltmeter.

2. VOLTAGE:

- (a) With voltmeter — within its range.
- (b) With voltmeter — above its range.
- (c) With voltmeter — below its range.

3. RESISTANCE:

- (a) Wheatstone bridge
 - (1) Where used.
 - (2) Apparatus required.
 - (3) Method of connection.
 - (4) Principle of operation.
- (b) Modifications of Wheatstone bridge:
 - (1) Slide-wire bridge.
 - (2) Kelvin Double Bridge.
- (c) Voltmeter-Ammeter method:
 - (1) Where used.
 - (2) Apparatus required.
 - (3) Method of connection.
 - (4) Calculations required.
- (d) Comparison of Voltmeter Deflections using Standard Resistance:
 - (1) Where used.
 - (2) Apparatus required.
 - (3) Method of connection.
 - (4) Theory.
- (e) Voltmeter method for Insulation Resistance:
 - (1) Where used.
 - (2) Apparatus required.
 - (3) Method of connection.
 - (4) Theory.

114 PRACTICAL ELECTRICAL ENGINEERING

(f) Direct Deflection method for Insulation Resistance:

- (1) Where used.**
- (2) Apparatus required.**
- (3) Method of connection.**
- (4) Operation and theory.**

4. POWER:

- (a) With Wattmeter.**
- (b) With Ammeter and Voltmeter.**
- (c) With Wattmeter and Ammeter and Voltmeter.**

5. ENERGY.

LESSON 5 — DIRECT-CURRENT MEASUREMENTS

1. Current

(a) *With ammeter.* As explained under "Electrical Instruments," it is necessary to connect an ammeter in series in a circuit, in order to measure the current flowing. If a shunt is used, this is put in series in the circuit, and the ammeter is then connected across the small terminals of the shunt. In order to protect the ammeter, a short-circuiting switch is often connected around the instrument. This switch is then kept closed, except when it is desired to take a reading. When the switch is opened, the full-current passes through the instrument.

(b) *With standard resistance and voltmeter.* In this case, a known standard resistance is connected in series in the circuit whose current is to be determined, and the voltage drop across the resistance is read on a low reading voltmeter, or millivoltmeter. Then, from equation (1), Ohm's Law, the current flowing is equal to the voltage reading divided by the resistance.

2. Voltage

(a) *With voltmeter — within its range.* In order to measure the difference of potential between any two points, it is simply necessary to connect the voltmeter between these two points. It should be noted that it is not necessary to break the circuit, when a voltage reading is desired, since

the voltmeter is shunted around the circuit whose voltage is to be measured.

(b) *With voltmeter — above its range.* If it is desired to measure a voltage higher than the range of the instrument, this may be done by inserting a known resistance in series with the voltmeter, or by using two identical voltmeters in series. Thus, if the voltmeter has a range of 150 volts, and it is desired to take readings on a 220-volt circuit, the following method may be adopted. If the total resistance of the voltmeter is 15,000 ohms, a resistance of 15,000 ohms may be connected in series with the instrument. Its range will then be doubled, since the actual voltage across the instrument will be half that across the circuit being measured. Hence, if the voltmeter reads 110 volts, this should be multiplied by two in order to get the e.m.f. of the circuit being measured. The same thing applies where an identical voltmeter is used in series with the instrument in the place of the resistance. In this case the two voltmeters will read the same, since with the same resistance there will be the same voltage drop across each, and hence the total voltage will be the sum of the two readings.

(c) *With voltmeter — below its range.* Although most voltmeters are provided with high and low-reading scales, it sometimes happens that a high-reading voltmeter is the only one available. This cannot be accurately read on low voltages. A method of obtaining an accurate reading, in this case, is to connect the voltmeter and the two points, whose voltage is to be measured, in series across a high potential source. Thus, if it is desired to measure the e.m.f. of a dry cell with a voltmeter, whose range is 150 volts, the two should be connected in series and both connected across

a higher potential circuit. Two readings are then necessary. A reading is first taken with connections as above. Suppose that in this case the voltmeter reads 108.6. A reading is next taken with the voltmeter connected alone across the higher potential source. If the voltmeter now reads 110, the voltage of the dry cell must have been equal to $110 - 108.6 = 1.4$ volts. If the cell had been connected in the reverse way, its voltage would have been added to the line voltage instead of being subtracted.

3. Resistance

(a) *Wheatstone Bridge:*

(1) *Where used.* The Wheatstone bridge is used for the accurate measurement of resistance, and has a wider range than any other method. It will give accurate results for all except extremely low and extremely high resistances. The fundamental principle of the Wheatstone bridge is used in all resistance testing sets, and modifications of the bridge are used for locating faults in cables, and also for the measurement of very low resistances. The Wheatstone bridge can also be used for measuring insulation resistance, up to about 2,000,000 ohms.

(2) *Apparatus required.* Three variable standard resistances, a galvanometer, and a primary battery are required. In Wheatstone bridges used for commercial work, the apparatus is usually contained in a hardwood case, and convenient means are provided for changing the known resistances, etc. Detailed wiring diagrams and descriptions of these commercial sets can be obtained from the manufacturers.

(3) *Method of connection.* The three known variable resistances and the unknown resistance are connected in a closed circuit, as in Fig. 23, which represents the theoretical Wheatstone bridge diagram. A battery and key are connected between *A* and *B*, while a galvanometer and key are connected between *C* and *D*. The battery generally consists of a few primary cells. The ratio arms

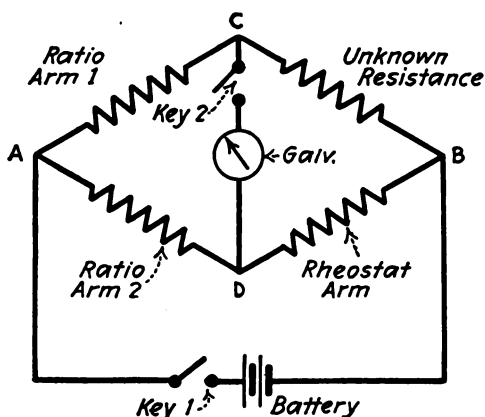


FIG. 23. — Theoretical Wheatstone bridge diagram.

usually contain coils whose resistances may be varied by multiples of 10. Thus ratio arm 1 may be varied so that its resistance is the same as ratio arm 2, or 10, 100, or 1000 times as great. In like manner, ratio arm 2 may be ad-

justed so that its resistance will be 10, 100, or 1000 times as great as arm 1. The various known resistance coils in the rheostat arm are of such value that any whole number may be obtained.

(4) *Principle of operation.* The battery current divides between the arms *ACB*, and *ADB*. No current will flow between *C* and *D*, provided points *C* and *D* are at the same potential. If current does flow between *C* and *D*, the galvanometer will deflect. The manipulation consists of adjusting the ratio arms and the rheostat arm until points *C* and *D* are at the same potential, or in other words, until the galvanometer no longer deflects. In this

case, the arms of the bridge are said to be balanced. Such a condition is always necessary when measuring the resistance, and since the method requires no deflection of the galvanometer, that instrument need not be calibrated. Assume that when the galvanometer key is closed, current flows from *A* to *B*. Also assume that the various known resistances are so adjusted that when the galvanometer key is closed, there is no deflection of the galvanometer. It is clear that there is then no difference of potential between *C* and *D*. Hence the voltage drop along ratio arm 1 must equal that along ratio arm 2. In like manner, the voltage drop along the unknown resistance must equal that along the rheostat arm. Then according to Ohm's Law, equation (2), the value of these voltage drops may be expressed in terms of current and resistance. Hence the above equalities may be expressed as follows:

$$\begin{aligned} \text{Current} \times \text{Resistance (Ratio Arm 1)} \\ = \text{Current} \times \text{Res. (Ratio Arm 2)} \end{aligned}$$

and

$$\begin{aligned} \text{Current} \times \text{Resistance (Unknown Resistance)} \\ = \text{Current} \times \text{Res. (Rheostat Arm)}. \end{aligned}$$

If the former equality is divided by the latter, the following equation is obtained:

$$\begin{aligned} \frac{\text{Current} \times \text{Res. (Ratio Arm 1)}}{\text{Current} \times \text{Res. (Unknown Res.)}} \\ = \frac{\text{Current} \times \text{Res. (Ratio Arm 2)}}{\text{Current} \times \text{Res. (Rheostat Arm)}}. \end{aligned}$$

Since no current flows through *CD*, the current in ratio arm 1 must equal the current in the unknown resistance.

Also, the current in ratio arm 2 must equal the current in the rheostat arm. Hence, these values will cancel out of the above equation, and the following equation will be obtained:

$$\frac{\text{Resistance Ratio Arm 1}}{\text{Unknown Resistance}} = \frac{\text{Resistance of Ratio Arm 2}}{\text{Resistance of Rheostat Arm}}$$

Hence, since three of the resistances are known, the unknown resistance can be found, by solving, as follows:

$$\text{Unknown Resistance} = \frac{\text{Resistance Ratio Arm 1}}{\text{Resistance Ratio Arm 2}} \times \text{Resistance Rheostat Arm.}$$

(b) *Modifications of Wheatstone Bridge:*

(1) *Slide-wire bridge.* In this type of bridge, a slide-wire

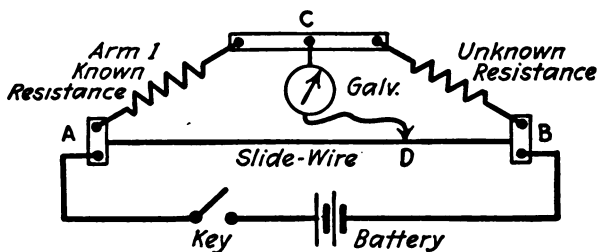


FIG. 24. — Slide-wire bridge diagram.

is used in place of the ratio arm 2 and the rheostat arm. This wire is of uniform resistance along its length, and is usually made of german-silver. A pointer is moved along the wire until the point is located where the galvanometer gives no deflection. In calculating the resistance, lengths of the slide-wire are used instead of actual resistances, since in this case, resistance is proportional to the length. Figure 24 shows a diagram of a

slide-wire bridge. When the bridge is balanced, and there is no deflection of the galvanometer, the unknown resistance may be calculated from the following equation:

$$\text{Unknown Resistance} = \frac{\text{Res. Arm 1} \times \text{Distance } DB}{\text{Distance } AD}.$$

In some cases, the resistance of arm 1 is made permanent, and a calibrated scale is placed under the slide-wire, so that the value of the unknown resistance may be read directly in ohms from the position of the pointer on the wire. Although the slide-wire bridge is not as accurate as the Wheatstone bridge, it is more convenient in certain cases, and allows of obtaining a quicker balance.

(2) *Kelvin Double Bridge.* This modification of the Wheatstone bridge is designed to measure the resistances of conductors of very low resistance, such as heavy copper bars, etc. The ordinary bridge would be inaccurate for this kind of measurement, since the contact

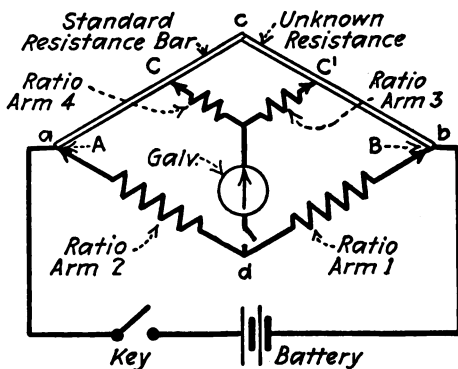


FIG. 25. — Theoretical diagram of Kelvin Double Bridge.

resistances may be much greater than the resistance to be measured. A theoretical diagram of the Kelvin double bridge is shown in Fig. 25. For commercial use, these bridges are arranged in convenient cases. Diagrams of connections are furnished by the makers. From the theoretical

diagram, it can be seen that the Kelvin double bridge is essentially a Wheatstone bridge in which one of the galvanometer connections is provided with two branches. One of these branches leads to the unknown resistance, cb , while the other one leads to a standard low resistance bar, ac . The contact points of these branches or ratio arms, may be moved along ac or cb , as indicated by the arrow-heads. In like manner, ratio arms 3 and 4 have adjustable contacts. In operating the bridge, it is first necessary to make the ratio of arms 2 to 1, the same as arms 4 to 3. Thus, if the ratio of arms 2 to 1 equals 100 to 1, the ratio of arms 4 to 3 must also equal 100 to 1. Next, adjustment is made so that the galvanometer gives no deflection. The usual method of making this adjustment is by varying the standard resistance ac . The ratio arms are so constructed that they give only a limited number of combinations. Provided that arms 1 and 2 are in the same ratio as 3 and 4, then, with no deflection of the galvanometer:

Unknown Resistance $C'B$

$$= \text{Standard Resistance } AC \times \frac{\text{Ratio Arm 1}}{\text{Ratio Arm 2}}.$$

It can be seen that this equation is the same as that used for the ordinary Wheatstone bridge. By the Double bridge methods, the contact resistances at a , b , c , and d are eliminated from the calculation, and hence resistances as low as 1/10,000 ohm may be accurately measured.

(c) *Voltmeter-Ammeter method:*

(1) *Where used.* This method can be used to measure resistances from 0.01 ohm to 500 or 600 ohms, but does not give very accurate results. It offers a comparatively

simple means of determining the resistances of armature and field windings of dynamos, etc.

(2) *Apparatus required.* An ammeter and a voltmeter are required for this test, and these should be accurately calibrated. A source of direct-current power is also necessary.

(3) *Method of connection.* The resistance to be measured should be connected in series with the ammeter and the source of power. For comparatively low resistances, the voltmeter should be connected at the terminals of the resistance, as in Fig. 26. In this case, there will be a slight error, due to the fact that the ammeter shows the sum of the currents in the resistance and in the voltmeter. However, if the voltmeter were connected around the ammeter, it would also indicate the fall of potential in the ammeter, and in the case

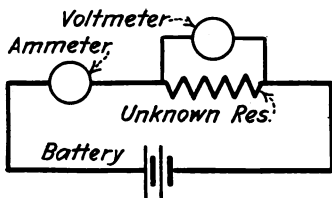


FIG. 26. — Measurement of comparatively low resistance by the voltmeter-ammeter method.

of a low resistance, this would introduce the greater error. For high resistances it is usual to connect the voltmeter around both the resistance to be measured and the ammeter. In such a case, the fact that the voltmeter current may be appreciable as compared with the current through the resistance, would cause a large error, if the voltmeter were connected directly across the resistance terminals.

(4) *Calculations required.* The resistance can be calculated from equation (3), in accordance with Ohm's Law. Thus, if the voltage reading is divided by the reading of the ammeter, the result will give the resistance of the conductor being measured. It is better to

take several readings and calculate the average resistance. Care should be taken to have all connections tight and also not to have the instruments too close. (They should be at least a foot apart to prevent magnetic interaction.)

(d) Comparison of Voltmeter Deflections using Standard Resistance:

(1) *Where used.* This method can be used wherever the Voltmeter-Ammeter method is applicable. Both of these methods are often referred to as "Fall of Potential" methods.

(2) *Apparatus required.* In this case, a voltmeter, a known or standard resistance and a source of power are necessary. For fairly accurate work the voltmeter should have a high resistance (especially in measuring low resistances), although it need not be calibrated provided the deflections are proportional to the voltage. The standard resistance should have sufficient carrying capacity to carry the current without heating and a steady current should be employed.

(3) *Method of connection.* The resistance to be measured is connected in series with the standard resistance and a few primary cells. The voltmeter is first connected across the known resistance and its deflection recorded. It is then placed across the unknown resistance and its deflection again recorded. (Same current must be flowing.)

(4) *Theory.*

The current flowing in the known resistance

$$= \frac{\text{Voltage across Known Resistance}}{\text{Known Resistance}}$$

(in accordance with Ohm's Law).

In like manner:

The current in the Unknown Resistance

$$= \frac{\text{Voltage across Unknown Resistance}}{\text{Unknown Resistance}}$$

Since the two resistances are in series, the current flowing in the known resistance will be the same as that flowing in the unknown resistance.

Hence:

$$\frac{\text{Voltage across Known Resistance}}{\text{Known Resistance}} = \frac{\text{Voltage across Unknown Resistance}}{\text{Unknown Resistance}}$$

Therefore:

Unknown Resistance

$$= \frac{\text{Known Res.} \times \text{Voltage across Unknown Res.}}{\text{Voltage across Known Resistance}}$$

Thus the value of the unknown resistance can easily be calculated from the two voltmeter readings and the known resistance.

(e) *Voltmeter method for Insulation Resistance:*

(1) *Where used.* This method may be used to determine the insulation resistance of transmission lines which are grounded at some point. Although insulation resistance cannot be accurately measured in this way, where there is no fault, this test is often convenient for finding out whether a certain high resistance comes within a given value.

(2) *Apparatus required.* A voltmeter of known resistance is required and also a source of power. This latter is not needed in measuring the insulation resistance of a

live line, or in determining the insulation resistance between the commutator and field frame of a generator in operation.

(3) *Method of connection.* The voltmeter is first connected directly across the source of power, and a reading taken.

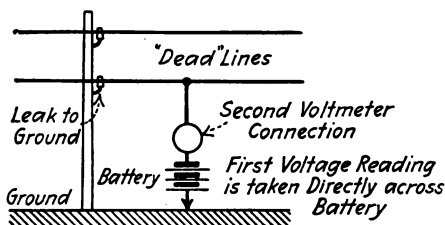


FIG. 27. — Connections for measuring insulation resistance of "dead" lines by the voltmeter method.

It is then connected in series with the resistance to be measured and the source of power, and a second reading is taken. Figure 27 illustrates the method of measuring insulation resistance

of "dead" lines; Fig. 28 shows method of measuring resistance of live lines. Figure 29 shows connections for

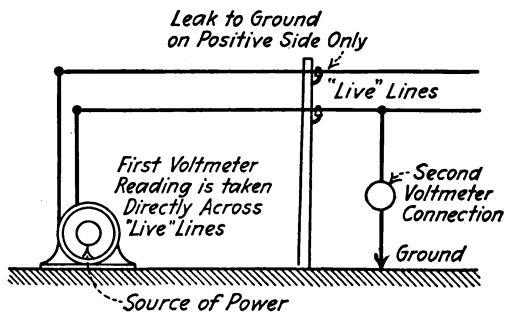


FIG. 28. — Voltmeter method for measuring insulation resistance of "live" lines.

determining insulation resistance between commutator and frame of a generator.

(4) *Theory.* With the voltmeter connected directly across the source of power, the reading will be proportional

to its resistance only. When connected in series with the insulation resistance and the source of power, the reading will be proportional to both these resistances. The principle is exactly the same as that explained under measurement of voltage (par. 2 (b)). If the resistance to be measured was of the same value as that of the voltmeter, the voltmeter deflection would be one-half that of the case where voltmeter was connected directly across source of power. However, since the insulation resistance is a great deal higher than the resistance of the voltmeter, the volt-

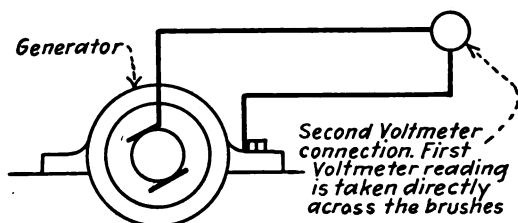


FIG. 29. — Connections for determining insulation resistance between the commutator and frame of a generator.

meter reading is comparatively low, when the two are connected in series. In other words, the two voltmeter readings are in the same proportion as the respective resistances. Expressed as an equality:

$$\frac{\text{Voltmeter Reading across Source of Power}}{\text{Voltmeter Reading when in series with source and Insulat. Resistance}} = \frac{\text{Resistance of Voltmeter}}{\text{Resistance of Voltmeter} + \text{Insulation Resistance}}$$

Since all values are known, in the above equation, with the exception of the insulation resistance, this may be solved, for, as follows:

$$\text{Insulation Resistance} = \text{Res. of Voltmeter} \times \frac{\text{V't'g R'ding in series with Source and Ins. Res.} - \text{V't'g R'ding across Source.}}{\text{Voltage Reading across Source of Power}}$$

(f) *Direct Deflection method for Insulation Resistance:*

(1) *Where used.* This method is used in large wire insulation factories for determining the insulation resistance of insulated wires. It is also in general use in this country in underground and submarine work. If the test is properly conducted accurate results can be obtained. Since only simple apparatus is necessary, this method is generally used in testing laboratories. It is

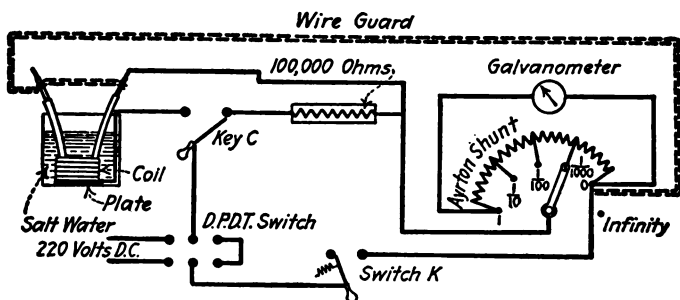


FIG. 30. — Connections for measuring insulation resistance by the direct deflection method.

sometimes referred to as “Insulation Test by Substitution.”

(2) *Apparatus required.* A shunted galvanometer (usually of the mirror type), a known high resistance (usually 100,000 ohms), a source of fairly high potential (about 220 volts direct current), a vessel for holding coil immersed in water, and suitably insulated switches are required.

(3) *Method of connection.* The apparatus is connected as shown in Fig. 30. The galvanometer shunt shown in the diagram is known as the “Ayrton” or “Universal” shunt. This type of shunt is generally used for this test, because it allows of better control of the galvanometer

deflections. Although the galvanometer used must be very sensitive, it should be heavily damped so that it will deflect slowly. The spring shown on switch *K* is used to keep galvanometer circuit open when readings are not being taken. The dotted line shows its position when the galvanometer is in use. Before starting the test, the coil of wire whose insulation is to be measured should be immersed in salt water for about 24 hours. During the test, the coil should be immersed in water, with the ends kept well back above the surface. The braid on the wire (if there is any) should be stripped back quite a distance. This is a protection, only when dry, the rubber being the effective insulator after coil has been soaked in water. The key *C* throws the insulation resistance of the cable into the circuit when thrown to the left. When the key is thrown to the right, the circuit is completed through the 100,000-ohm resistance. The power supply is connected at the double-pole double-throw switch. When this switch is thrown to the right, the cable is discharged. The negative side of the line must be connected to the conductor in order to get accurate results. The polarity may be tested for with a voltmeter. Another precaution necessary to insure accurate results is the use of a guard wire. This is used, in order to allow only current meant for the galvanometer to flow through it. The guard wire should be wrapped around the insulation at the conductor ends, and connected to the supply side of the shunt and the galvanometer. The double dotted line shows the connections of the guard wire in the figure. Care should always be taken to have all apparatus extremely well insulated.

Since the voltage of the supply is about 220, caution should be used in connecting up the apparatus, to keep it safe from damage. A constant voltage is necessary during the test.

(4) *Operation and theory.* In accordance with Ohm's Law, the greater the resistance in the galvanometer circuit, the less the current (with constant e.m.f.). Hence, the deflections of the galvanometer will vary inversely as the resistance of the galvanometer circuit. Thus, with a constant applied e.m.f., a certain deflection will be obtained when the resistance of 100,000 ohms is connected in series with the galvanometer. A smaller deflection (inversely proportional to the increase of resistance) will be obtained when the insulation resistance is put in series with the galvanometer. In order that the resistance may be determined in megohms (a megohm is equal to one million ohms), it is necessary to know how many megohms will cause a deflection of one division on the galvanometer scale. This value is called the "constant" of the apparatus. Thus, for example, if the constant of the apparatus was 5000, this means that a deflection of one scale division indicates a resistance of 5000 megohms in the galvanometer circuit. Then, the greater the deflection, the less the resistance in the circuit. Thus, with the above constant, a deflection of 5 scale divisions would indicate a resistance of 1000 megohms. Hence, once the constant is found, it is simply necessary to substitute the insulation resistance, in the place of the 100,000 ohms, and read the deflection on the galvanometer scale. Dividing the constant by the deflection then gives the value of the insulation resistance in megohms.

Since an extremely sensitive galvanometer is used, it is necessary to damp it. This requires the use of a shunt. The shunt complicates the calculation slightly. Before explaining the theory of the Ayrton shunt, the use of a simple shunt will be taken up. When an ordinary shunt is used to determine the constant of the apparatus, it is necessary to know the resistance of the galvanometer and also the resistance of the shunt. Assume that the galvanometer resistance equals 4000 ohms, and the shunt resistance equals 10 ohms. Since the two are in parallel, the current will divide inversely in proportion to their resistance. Thus, by using a low-resistance shunt, most of the current will flow through it. In this case, 400 times as much current will flow through the shunt as through the galvanometer. Thus, with the current of 401 milli-amperes (a milliamperere is equal to $1/1000$ th of an ampere), 1 milliamperere would flow through the galvanometer, and 400 times as much, or 400 milliamperees would flow through the shunt. Hence, the ratio of the current which will flow through the galvanometer to the total current will be 1 to 401. Therefore the multiplying power of the shunt in this case, is 401. To illustrate the calculation, in determining the constant of the apparatus, suppose that the above shunt were used and that the galvanometer were connected in series with the 100,000-ohm resistance and the source of power, and that a deflection of 50 scale divisions was obtained. Since the multiplying power of the shunt is 401, it is clear that 401 times as much current would flow through the galvanometer if it were unshunted, and hence the theoretical deflection in this case would be $50 \times 401 = 20,050$ scale divisions.

Hence, 20,050 divisions correspond to a resistance of 100,000 ohms in series in the galvanometer circuit. A resistance 10 times as great (1,000,000 ohms or a megohm) would give a deflection one-tenth as small. Hence 2005 divisions would be the deflection corresponding to 1 megohm. Hence, a deflection of 1 scale division would correspond to 2005 megohms in series in the galvanometer circuit, and this is the "constant" of the apparatus.

The Ayrton shunt is usually used instead of the ordinary shunt, since it allows of a number of convenient adjustments, and moreover, it is not necessary to know the actual resistance either of the shunt, or of the galvanometer. When the shunt is set at 1, its connection is the same as any other shunt, and its multiplying power will depend upon the relative resistance of itself and that of the galvanometer. When the arm is moved to the other contacts, resistance is added to the galvanometer, and taken away from the shunt so that less current flows through the galvanometer. It can be seen from the diagram of connections that no matter how much resistance is added to the galvanometer side, the same amount must be subtracted from the shunt side. Thus, there is a definite ratio between the current flowing in the galvanometer when the arm is at 1 and when it is at any other contact point, and this ratio holds, regardless of the resistance either of the shunt or of the galvanometer. The arrangement is such that at the second contact point to the right one-tenth as much current will flow through the galvanometer as when the arm is at the extreme left; at the third contact point to the right, one one-hundredth as much current will flow through the galvanometer as when

the arm is at the extreme left, etc. Thus, by simply moving the arm from one contact point to another, it is possible to vary the current in the galvanometer, in multiples of 10, regardless of the actual ratio between current in the line and current in the galvanometer. As an illustration, suppose it is desired to find the constant of the apparatus, in Fig. 30 using the Ayrton shunt. With the shunt at its lowest resistance value, one one-thousandth (connection shown in figure), the switch *K* is thrown to the left, thus short-circuiting the insulation resistance and throwing the 100,000 ohms in series with the galvanometer and the source of power. Assume again that the deflection is 50 scale divisions. If the arm of the shunt had been on 1, at the extreme left, the theoretical deflection would have been 1000 times as great, or 50,000, since in that case 1000 times as much current would have flowed through the galvanometer. Thus, with a resistance of 100,000 ohms in series with the galvanometer, there is a theoretical deflection of 50,000 divisions. The corresponding deflection with 1,000,000 ohms would be 5000 divisions. Therefore, a deflection of one scale division would correspond to 5000 megohms in the circuit, and hence 5000 is the constant of the apparatus.

To measure the value of the insulation resistance, the switch *C* is thrown to the left so that the insulation resistance is in series with the galvanometer. The insulation resistance should be in the circuit 60 seconds before closing the galvanometer switch *K*. The Ayrton shunt is next adjusted until a readable deflection is obtained. If the spot goes off the scale the arm of the shunt must be moved so that there is less resistance in the shunt and

more in series with the galvanometer. If the reading is too low the arm must be moved in the opposite direction to get the reverse effect. Thus, if the arm is at the one one-hundredth contact point, and the spot goes off the scale, the arm must be moved to the one one-thousandth point and the deflection again noted. In measuring the insulation resistance of long cables, the deflection will probably be large at first, then decreasing in value. To save time, it is usual to observe the deflection at a fixed time after closing the switch, usually one minute after the galvanometer switch has been closed. Assume that with a galvanometer constant of 5000, as determined above, a deflection of 10 scale divisions is noted at the end of one minute's electrification, and with the Ayrton shunt at the one-tenth contact point. The theoretical deflection at contact point "one," would then be ten times as great, or 100 scale divisions. This corresponds to an insulation resistance of $5000/100 = 50$ megohms. If the length of coil measured equaled one-half mile, then the insulation resistance of this cable per mile is equal to $50/2 = 25$ megohms. The longer the coil, the less the insulation resistance, since this resistance is in parallel, and the area of current leakage increases directly with the length. In the above case, if the shunt had been at the one one-hundredth contact point, instead of the one-tenth, the deflection would have been only 1 scale division. However, the same final result would have been obtained. Although the insulation resistance may be obtained from the one reading, it is better to keep the current on for about five minutes, taking readings at the end of each minute. It will be found that the readings decrease gradually. At the end of the five minutes, the

double-throw switch should be thrown to the right, thus discharging the cable. After it has been fully discharged, readings should again be taken as above, but with the current reversed.

4. Power

(a) *With Wattmeter.* The power being consumed in a circuit can be read directly in watts or kilowatts, on this instrument. The usual method of connection is shown in Fig. 31. The heavy terminals connect to the current element and should be connected in series in the circuit.

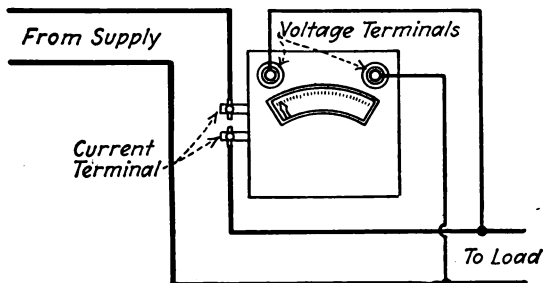


FIG. 31. — Usual connections for measuring power by means of a wattmeter.

The light terminals are the voltage connection and should be connected in parallel. Care should be taken, not to connect the current terminals across the line.

(b) *With Ammeter and Voltmeter.* Since electrical power is the product of amperes times volts, the power consumed in a direct-current circuit may be determined by taking readings with an ammeter and a voltmeter, and multiplying these readings together. This method is often used where a wattmeter is not available.

(c) *With Wattmeter and Ammeter and Voltmeter.* Where the wattmeter and the ammeter and voltmeter are to be

used in the same circuit, for the measurement of power (as when calibrating) there are a number of methods of con-

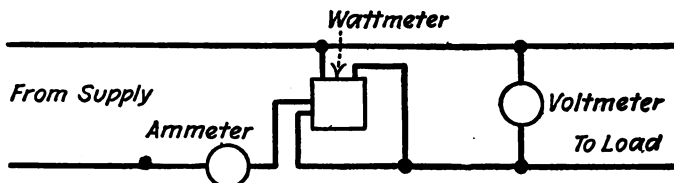


FIG. 32. — One method of connecting ammeter, voltmeter and wattmeter in a circuit for measurement of power.

nection. Three different methods are shown in Figs. 32, 33, and 34. Figures 32 and 33 show the usual methods of connection. The ammeter reading in both these methods

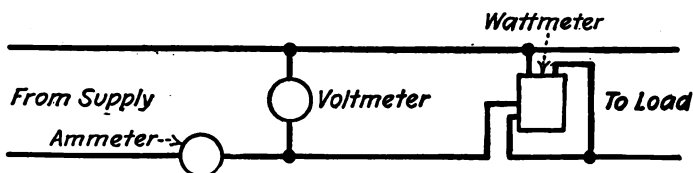


FIG. 33. — Another common method of connecting ammeter, voltmeter and wattmeter in a circuit for measurement of power.

is the sum of the load current plus the current in the voltage coils of the wattmeter and in the coils of the voltmeter. Since the current in these coils is negligible, except where

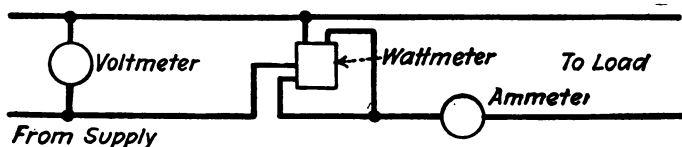


FIG. 34. — A third method of connecting ammeter, voltmeter and wattmeter in a circuit for measurement of power.

measuring very small currents, it is usually unnecessary to correct the ammeter readings. In the method of connection shown in Fig. 33 a slight error is caused by the fact that

the voltmeter reads a higher voltage than that actually applied to the load. This is due to the drop in voltage in the current coil of the wattmeter. Figure 34 shows the best method of connection for getting an accurate reading of current. However, in this case, if very accurate wattmeter readings are required, it is necessary to subtract the losses in the ammeter and in the voltage coil of the wattmeter.

5. Energy

Watt-hour meters furnish the usual means of determining the amount of electrical energy being expended. These instruments are usually calibrated in kilowatt-hours. There are usually four terminals on the watt-hour meter, two of which are marked for connection to the line and two being marked for connection to the load. However in some types of watt-hour meters, especially those of larger capacity, there are only three terminals on the instrument. Diagrams of connection are

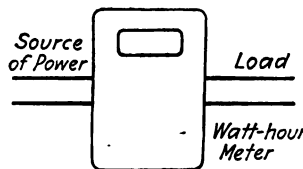


FIG. 35. — Usual method of connecting a watt-hour meter in a circuit for measuring energy.

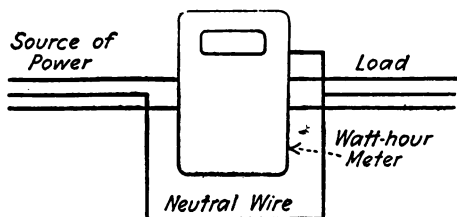


FIG. 36. — Method of connecting watt-hour meter where three-wire system is used.

shown in Figs. 35 and 36. Figure 36 shows method of connection where the three-wire system is used. Service watt-hour meters are often calibrated by means of

a standard indicating wattmeter and a stop watch. In the testing laboratories, it is usual to calibrate the watt-hour

meter by means of a voltmeter, an ammeter and a stop watch. In general the method employed is to connect these instruments up to the same load, Fig. 20 (*a*), and to calculate the actual energy expended from the readings of the stop watch, the voltmeter and the ammeter. At the same time and for the same time interval, (about a minute), the revolutions of the watt-hour meter are counted. By means of the constant marked on the brake disc, the reading of the meter can be determined. If the value thus calculated is higher than that determined by means of the voltmeter, ammeter, etc., the watt-hour meter is going too fast and must be adjusted.

Outline of Lesson 6 — PRIMARY AND SECONDARY (STORAGE) CELLS

1. PRIMARY CELLS:

(a) Definitions:

- (1) Primary cell.**
- (2) Electrolyte.**
- (3) Plates or Electrodes.**
- (4) Poles or Terminals.**
- (5) Cell.**
- (6) Battery.**

(b) Principle of Operation.

(c) Polarization:

- (1) Explanation of action.**
- (2) Prevention of polarization.**

(d) Local Action.

(e) E.m.f. of cells:

- (1) Open circuit.**
- (2) Closed circuit**

(f) Factors determining internal resistance of cells:

- (1) Constant factors.**
- (2) Variable factors.**
- (3) Determination of internal resistance.**
- (4) Determination of total or working resistance**

(g) Classes of cells:

- (1) Open-circuit cells.**
- (2) Closed-circuit cells.**

(h) Uses:

- (1) Open-circuit cells.**
- (2) Closed-circuit cells.**

(i) Description of various types of cells:

- (1) Leclanche cell.**
- (2) Gravity or Crowfoot cell.**

(j) Batteries:

- (1) Series arrangement of cells.**
- (2) Parallel or multiple arrangement of cells.**
- (3) Series-parallel arrangement of cells.**
- (4) Arrangement of cells for Highest Efficiency.**
- (5) Arrangement of cells for Maximum Current.**

2. SECONDARY OR STORAGE CELLS:

- (a) Definition.**
- (b) Principle of operation.**
- (c) Types of Storage Cells:**
 - (1) Lead cells.**
 - (2) Nickel-Iron-Alkaline cell (Edison cell)**
- (d) Capacity of storage cells.**
- (e) Uses of storage batteries.**

LESSON 6 — PRIMARY AND SECONDARY (STORAGE) CELLS

1. Primary Cells

(a) *Definitions:*

(1) *Primary cell.* The primary cell is a device for transforming chemical energy into electrical energy. It consists of two different conductors, immersed in a liquid which acts chemically on one conductor, or on one more than the other, thus maintaining the difference of potential between them. During this action, one of the conductors wears away, and the liquid is also consumed. These can usually be replaced.

(2) *Electrolyte.* This is the name of the liquid used in the primary cell. This liquid may be either an acid or a salt solution. The electrolyte serves to increase the difference of potential between the conductors immersed in it, and moreover, its action is such that the difference of potential is maintained during the chemical action.

(3) *Plates or Electrodes.* These are the conductors which are immersed in the liquid. The current flows from the positive plate or "anode," through the electrolyte to the negative plate or "cathode." The anode is usually made of zinc.

(4) *Poles or Terminals.* These are the ends of the plates not immersed in the electrolyte. They are used in making connections with the external circuit. As stated above, the current flows through the electrolyte from the positive

to the negative plate. Hence, it completes the circuit through the external conductor by passing from the terminal or pole of the negative plate to the pole of the positive plate. For this reason, the pole of the negative plate is said to be a "positive" pole, while the pole of the positive plate is called the "negative" pole. According to the conventional use of the terms, current always flows from positive to negative. To avoid confusion, it should be kept in mind that when referring to the poles, the external circuit is under consideration, while when referring to the plates, the circuit through the electrolyte is being considered.

(5) *Cell*. The term cell is sometimes used to denote the vessel which contains the conductors and the electrolyte. Usually, however, it refers to the entire device, as defined under "primary cell."

(6) *Battery*. A battery consists of a combination of properly connected cells. The term battery is sometimes incorrectly used to denote a cell.

(b) *Principle of operation*. When an electrical conductor, such as a piece of metal, is placed in a liquid, this conductor becomes of higher or lower potential than the liquid. If two conductors are immersed in an electrolyte, not touching each other, and of such materials that one is of higher potential, and the other of lower potential, than the liquid, the device will constitute a source of electrical energy.

When the two conductors are connected externally, electricity must flow, since there is an appreciable difference of potential maintained between them. The transformation of energy apparently takes place at that part of the anode which is in contact with the electrolyte. When current

flows, due to the difference of potential between the anode and the cathode, its passage through the electrolyte breaks up the electrolyte into various elements. Some of these unite with or "attack" the anode, thus "eating" it away.

(c) *Polarization:*

(1) *Explanation of action.* The electric current liberates hydrogen from the electrolyte in passing through it. The hydrogen is carried to the negative plate, along with the current, and collects there. The presence of the hydrogen increases the internal resistance of the cell. Hence it is harder for the current to pass through it, and as a result the e.m.f. available at the terminals is materially lowered. Moreover, there is a small difference of potential between the negative plate and the hydrogen which acts in opposition to the e.m.f. of the cell. This further reduces the available e.m.f. The result of this reduction of the e.m.f. of the cell by polarization may be such that it will be impossible to cause current to flow.

(2) *Prevention of polarization.* Polarization may be counteracted or prevented by the use of "depolarizers." These are of three general classes:

Chemical depolarizers. These consist of some substance which combines readily with the hydrogen. This substance is placed in the cell near the cathode. When the hydrogen touches this substance, it combines with it to form a new compound. Among the substances commonly used for this purpose are manganese dioxide, potassium bichromate, nitric acid, and cuprous oxide.

Electrochemical depolarizers. These consist of a substance which, when used with proper electrodes and

electrolyte, results in a metal, such as copper, being liberated at the cathode instead of hydrogen. Hence, with no hydrogen free in the electrolyte, there can be no polarization.

Mechanical depolarizers. These are simply mechanical means of sweeping or blowing the hydrogen away from the cathode. They are the least effective of the three classes and are least used. In some cells, the only means of preventing polarization is to have the surface of the cathode roughened. Of course, such a method is only a makeshift.

(d) *Local Action.* Local action is electrochemical action within the cell, usually at the positive plate, which does not add to the useful output. As mentioned above, zinc is the material usually employed for the positive plate. This zinc practically always contains impurities such as carbon, iron, etc. When the zinc is immersed in the electrolyte, there is a difference of potential between the zinc and the impurities and small local currents flow from the zinc through the electrolyte to the impurities and back to the zinc again. These currents serve no useful purpose and moreover use up the zinc and the electrolyte. Local action can be practically eliminated by coating the surface of the zinc with mercury. This is called "amalgamation."

(e) *E.m.f. of cells:*

(1) *Open circuit.* The potential difference between the terminals of a cell, on open circuit, is equal to the total voltage developed within the cell. This total voltage depends upon the following things only: the materials of the electrodes and of the electrolyte. It is independent of the size, shape, or other physical properties. The

reason for this, as explained under "Principle of Operation," is that every conductor has a fixed potential with reference to the electrolyte in which it is immersed. Thus, as an example, when zinc and copper are the materials of the electrodes, and sulphuric acid the material of the electrolyte, the total voltage developed within the cell will always be about 1 volt. The open-circuit voltage of a cell may be measured with sufficient accuracy by means of a low-reading voltmeter. In this case, the resistance of the voltmeter is so high, that no appreciable current flows, and hence the reading is correct enough for practical purposes. Where great accuracy is necessary, the voltage is obtained by balancing against a standard cell, using an instrument called a "potentiometer." The measurement can be made in this way, with no current flowing in the circuit.

(2) *Closed circuit.* When current is being drawn from the cell, and the voltage is measured, it will be found to be lower than on open circuit. This drop in voltage is caused by two things. One is the internal resistance of the cell. This is practically constant for any particular cell. The other is polarization. As explained above, this varies with the degree of use. The total effect of these two things is to increase the working resistance of the cell, thus reducing the available voltage at the terminals. In accordance with Ohm's Law, the drop in voltage within the cell will equal the product of the current flowing times the working resistance.

(f) *Factors determining internal resistance of cells:*

(1) *Constant factors.* Certain materials in use as electrodes and electrolytes have more resistance than others. The

farther apart the electrodes are placed, the greater the resistance. The resistance within a cell can be reduced by having a greater area of the electrode in contact with the electrolyte. The use of a depolarizer sometimes increases the resistance.

(2) *Variable factors.* The internal resistance will vary to a certain extent with the temperature and the density of the electrolyte.

(3) *Determination of internal resistance.* In order to determine the internal resistance of a cell (separate from the polarization effect, which acts in the same way as resistance), it is necessary, according to one method, to insert the cell as one of the arms of a Wheatstone bridge. (See Lesson 5 — par. 3 (a).) It should be noted that the cell is put in the place of the unknown resistance. No other source of power is needed and the place where the battery ordinarily is connected is simply bridged across with ordinary leads. (See Fig. 23.) Ratio arm 1 should be as low as possible. Ratio arm 2 should be as high as possible. With key 2 closed and key 1 open, current flows through the galvanometer and the needle will be deflected. The rheostat arm should be set at about 1000 ohms, and ratio arm 2 should be adjusted until opening and closing of key 1 produces no change in the galvanometer deflection. In this case, points *A* and *B* must be at the same potential, and therefore:

Resistance of Cell

$$= \frac{\text{Res. Ratio Arm 1} \times \text{Res. Rheostat Arm}}{\text{Res. Ratio Arm 2}}$$

(4) *Determination of total or working resistance.* When the cell is supplying current to an external circuit, the

internal resistance is apparently increased, due to the action of polarization. The working resistance can be determined in the following way: The open circuit voltage of the cell is obtained with a voltmeter. The cell is next connected in series with an ammeter, forming a closed circuit, and the voltage is again read. It will be found that there has been a considerable drop in voltage. The difference between the two voltmeter readings will give the amount of this drop. Since this drop in voltage has been caused by the combined effects of internal resistance and polarization, it is a simple matter to determine the value of the resistance causing such a drop. The current in the circuit is known from the ammeter reading, and hence, in accordance with Ohm's Law, the working resistance is equal to the drop in voltage divided by the current flowing.

(g) *Classes of cells.* Primary cells may be divided into two general classes:

(1) *Open-circuit cells.* Cells which are designed for intermittent use only, are classed as open-circuit cells. These cells usually have a depolarizer which acts slowly. In some cases no depolarizer is used. The cells are meant for use during short intervals of time only, and must stand for long periods on open circuit, during which the hydrogen is gradually removed from the negative plate. If the rest periods are not long enough or frequent enough, the operation of these cells will not be satisfactory. It is important that local action be entirely eliminated in these cells. Common examples of open-circuit cells are the dry cell, and the Leclanché cell.

(2) *Closed-circuit cells.* These cells are designed for

steady use over a considerable period of time. They differ from the open-circuit cells, in that their depolarizer is quick acting, thus allowing no hydrogen to collect on the negative electrode. Certain closed-circuit cells, such as the Fuller or Edison-Lalande, can be used for intermittent work also, but most closed-circuit cells cannot be left on open circuit for any length of time because of the chemical action between the depolarizer and the electrolyte. The Gravity cell and the Bichromate cell, are examples of closed-circuit cells.

(h) *Uses:*

(1) *Open-circuit.* Electric bells; certain classes of telephone work; signaling; annunciators; etc.

(2) *Closed-circuit.* Telegraph work; closed-circuit burglar-alarms; block signaling; small lights or motors; etc.

(i) *Description of various types of cells.* A description of the construction, characteristics, and chemical actions of the various types of primary cells is beyond the scope of this book. Exact data can be obtained from any electrical handbook. However, an open-circuit cell, and a closed-circuit cell, will be described, as typical examples.

(1) *Leclanché cell.* The anode or positive electrode of this cell is made of zinc, which is usually amalgamated. The zinc is sometimes cylindrical in form, so as to partially enclose the negative plate, but the more usual form is the stick form, somewhat resembling a lead pencil. The cathode or negative plate is made of carbon. Various manufacturers employ several different methods of shaping the carbon, thus giving rise to a difference in internal resistance. The carbon is usually in the form of a hollow cylinder. Manganese dioxide and powdered

carbon are placed within the carbon cylinder. The manganese dioxide acts as the depolarizer and also increases the difference of potential between the electrodes. The powdered carbon adds to the conductivity. The electrolyte usually consists of ammonium chloride (sal ammoniac) dissolved in water. The elements are contained in a glass jar, coated at the top with paraffin. This coating serves to prevent creeping of the salts. The top of the jar is usually provided with a carbon cover, but in some cases the cover is of hard rubber or wood. Leclanché cells have an open-circuit voltage of about 1.5 volts. The internal resistance (total) varies from .5 up to 4 ohms. These cells are especially adapted for bell work where the current required is intermittent. They cannot be used for closed-circuit work.

The chemical action taking place in the cell is as follows: The sal ammoniac solution acts upon the zinc to form a salt called zinc chloride. Ammonia gas is liberated by this action and part of this dissolves in the liquid, while part escapes. Hydrogen is also freed from the sal ammoniac, and this combines with the oxygen obtained from the manganese dioxide, thus forming water. This formation of water goes on, even when the cell is not being used, and this accounts for the depolarizing action of the manganese dioxide. The manganese dioxide is reduced by this action to another manganese salt, having less oxygen in it. There is no change in the carbon plate, but the zinc electrode gradually is worn away by the chemical action.

The dry cell is a modification of the Leclanché cell. In this cell, the amount of the electrolyte is reduced to a

minimum, simply enough being used to saturate the blotting paper which separates the zinc anode from the carbon cathode. Zinc chloride solution is usually mixed with the sal ammoniac. In this cell, the zinc also acts as the containing vessel.

(2) *Gravity or Crowfoot cell.* The positive electrode of this cell is made of zinc, shaped somewhat like a crowfoot (whence the name). The reason for this shape is to increase the surface of the zinc in contact with the electrolyte. The terminal of the zinc hooks over the edge of the glass jar container, in such a way that the crowfoot is suspended in the top of the electrolyte. The cathode is of copper. The copper consists of several layers, fastened in the middle by copper rivets, and spread out in sort of a star shape. The copper is set on edge in the bottom of the vessel. The terminal connection is provided by means of a rubber-covered copper wire coming up through the solution. The electrolyte consists of a zinc sulphate solution. The depolarizer is a copper sulphate solution which remains in place around the copper due to the action of gravity (since the specific gravity of the copper sulphate solution is greater than that of the zinc sulphate). In setting up the cell, the copper sulphate (blue vitriol) crystals are poured in after the copper cathode has been set on edge on the bottom of the jar. The zinc is then hung on the top and the jar is filled with water until the zinc is covered. A tablespoonful of sulphuric acid is then added. A solution of copper sulphate forms around the copper. After use, a zinc sulphate solution is formed around the zinc. This latter solution floats above the copper solution, as

mentioned above. The specific gravity of the zinc sulphate should not exceed 1.15. In order to hasten the formation of zinc sulphate, as well as to reduce the internal resistance, the cell should be short-circuited for a few days after setting up. A blue line will indicate the plane of separation between the two solutions. This should be about one-half the distance between the electrodes. In some cases a mineral oil (non-inflammable under 400 degrees F.) is poured over the top of the zinc sulphate to prevent evaporation. This also prevents creeping of the salts over the sides of the jar. Where no oil is used, creeping can be prevented by coating the top of the jar with paraffin. The temperature of the cell should be kept above 70 degrees F. in order to prevent an undue rise in the internal resistance. The gravity cell is suitable for closed-circuit work only. The voltage on open-circuit is about 1.07. The internal resistance varies from 1 to 3 ohms. These cells give best results where a current of about 1 ampere is being drawn.

The chemical action of the gravity cell is as follows: The sulphuric acid acts upon the zinc, thus forming zinc sulphate. Hydrogen is liberated during this action. The hydrogen is carried along with the current towards the negative electrode, but as soon as it comes in contact with the copper sulphate it frees the copper from the solution and forms sulphuric acid. The pure copper thus liberated is deposited on the copper plate. Hence, polarization is entirely prevented in this cell by electrochemical action. The copper sulphate crystals dissolve as the chemical action weakens the solution, thus tending to keep the solution constantly saturated.

Cells of the gravity type (there are a number of variations and modifications) are adapted to all forms of light closed-circuit work such as closed-circuit signaling, telephone, and telegraph work, burglar alarms, etc.

(j) *Batteries:*

(1) *Series arrangement of cells.* The "series" circuit has been defined in Lesson 3 — par. 1 (f) (4). As stated under section (4), when cells are connected in series, so that the positive terminal of one connects to the negative terminal of the other, then the total voltage will equal the sum of the separate voltages. As an illustration, assume that three exactly similar cells are connected in series, and aiding each other — also assume that each cell gives a voltage of 1.5 volts and has an internal resistance of 2 ohms and that the external circuit connected in series with this battery consists of a resistance of 94 ohms. To determine the total voltage of the battery, the total internal resistance, and the current which will flow through the circuit:

The total voltage will be $3 \times 1.5 = 4.5$ volts.

The total internal resistance can be found, in the same manner as for any other series circuit, by adding up the separate internal resistances. In this case it is equal to 2 plus 2 plus 2 = 6 ohms.

The current flowing in the circuit is found by Ohm's Law. Since the external resistance is equal to 94 ohms and the total internal resistance is equal to 6 ohms, the resistance of the entire circuit is equal to 94 plus 6 = 100 ohms; hence according to equation (1):

Current flowing

$$= \frac{\text{Total Voltage}}{\text{Total Resistance}} = 4.5/100 = 0.045 \text{ ampere.}$$

It should be noted that in the series arrangement of cells, the internal resistance (total) and hence the total resistance of the circuit, is increased by a small amount with each additional cell. If the resistance of the external circuit is small as compared with that of the cells the series arrangement will not give the best results. On the other hand, if the external resistance is comparatively high, the increase in the total resistance, due to the addition of more cells in series, will be negligible, while the increase of e. m. f. will aid in sending the current through the resistance of the circuit. Hence the series arrangement is the proper one where the external resistance is high.

(2) *Parallel or multiple arrangement of cells.* For definition of a "parallel" circuit see Lesson 3 — par. 1 (f) (5). When cells are connected in parallel — with all the positive terminals connected together, and all the negative terminals connected together, there is no increase in the total voltage. However, as in any other parallel circuit, parallel arrangement of cells results in a reduction of the total internal resistance. As an illustrative example, assume that the three cells of the problem above (1.5 volts each, internal resistance 2 ohms each) are connected in parallel and that this parallel arrangement is connected in series with an external resistance of $\frac{1}{2}$ of an ohm. To determine the total internal resistance, and the total current flowing through the circuit:

Since the arrangement of cells constitute a parallel circuit, it is more convenient to deal with conductances, in calculating the total internal resistance. The conductance of each cell is $\frac{1}{2}$. Hence the total conductance

of the three cells is $3/2$. The total resistance, therefore, is equal to the reciprocal of this and is equal to $\frac{2}{3}$ ohm.

To find the total current flowing: the total voltage is equal to 1.5 volts. The total resistance of the circuit is equal to the internal resistance (total) $\frac{2}{3}$ plus the external resistance, $\frac{1}{3}$ ohm = 1 Ohm total. Hence, according to equation (1):

$$\text{Current Flowing} = 1.5/1 = 1.5 \text{ amperes.}$$

The more cells there are connected in parallel, the less will be the internal resistance (total) and the greater will be the current capacity. Where the external resistance is comparatively small, the parallel arrangement is advantageous, since it results in a material reduction of the resistance of the entire circuit. The parallel battery is usually employed where a heavy current is required, but at a low voltage.

(3) *Series-parallel arrangement of cells.* Such circuits are explained in Lesson 3 — par. 1 (f) (6). Series-parallel arrangement of cells is generally resorted to where a higher voltage is needed than obtainable with parallel arrangement, and where the added current capacity of the parallel connection is a necessity. In calculating the total internal resistance, it is better to calculate the series and the parallel parts separate. Thus, as an example, assume that two sets or groups, of two cells each are arranged in a parallel-series combination. That is to say, that the two cells in each group are in series, while the two groups are in parallel. Assume voltage of each cell 1.5 volts; internal resistance 3 ohms. To determine total internal resistance of the combination; also total voltage:

Since there are two cells in series in each branch or group, the total resistance of each group = $3 + 3 = 6$ ohms. Hence there are two branches of 6 ohms each in parallel. Adding the conductances of these branches $\frac{1}{6} + \frac{1}{6}$, gives a total conductance of $\frac{1}{3}$ or a total resistance of 3 ohms. Hence, in this case, the total resistance is no more than that of a single cell.

The total voltage is simply the voltage of the cells in series = $1.5 + 1.5 = 3$ volts.

(4) *Arrangement of cells for Highest Efficiency.* The efficiency of a battery is the ratio between the total useful power and the total power developed. Since the lost power is consumed in the internal resistance of the battery, it is clear that the arrangement which will give least internal resistance will also give highest efficiency and most economical operation. The parallel arrangement is the one which gives the smallest possible internal resistance.

(5) *Arrangement of cells for Maximum Current.* It can be proven both experimentally and mathematically that the best arrangement of cells for obtaining a maximum current flow through a given resistance, is that in which the total internal resistance of the battery is equal to the external resistance. When cells are thus arranged to give maximum current the efficiency will be about 50 per cent.

2. Secondary or Storage Cells

(a) *Definition.* A storage cell (also called "accumulator" and "secondary cell") consists of a positive and a negative electrode, immersed in an electrolyte which becomes active, only after the passage of an electric current. The electrodes

are of metal or of a metallic compound. When an electric current is sent into a secondary cell certain chemical actions take place whereby electrical energy is transformed into chemical energy. This process is termed "charging." After the cell is charged, the action is reversed, chemical energy is transformed into electrical energy and the cell is capable of delivering an electric current to an outside circuit. This is called "discharging." The cell does not store electricity. However, its nature is such that it holds or stores the chemical energy ready for instantaneous transformation into electrical energy. In commercial cells several positive plates are connected in multiple to form one positive electrode, and several negative plates are connected in multiple to form one negative electrode. The term "storage battery" refers to a combination of two or more storage cells.

(b) *Principle of operation.* The principle of operation of the storage cell is the same as that of the primary cell. As in the primary cell, the metals when immersed in the electrolyte differ appreciably in potential. There is this difference, however, that action in the secondary cell will not take place until after charging. Thereafter, the chemical action maintains the difference of potential until the stored energy has been used up. In the primary cell the electrical energy is derived by consuming the positive electrode, and after this has been used up, it must be replaced. In the secondary cell the negative plate is used to a certain extent during discharge, but it is replaced electrochemically during charge, by the passage of the current through the electrolyte in the reverse direction to that of discharge. It is theoretically possible to restore the negative electrode

of a primary cell by sending in current from an outside source. However, this process is expensive and not commercially feasible.

(c) *Types of Storage Cells:*

(1) *Lead cells.* In lead cells, the positive electrode is of lead peroxide, the negative electrode is of spongy lead, and the electrolyte is of dilute sulphuric acid. It should be noted that within the cell, on discharge, the current passes from the spongy lead to the lead peroxide plate. Hence the names positive and negative as applied above, refer to the external circuit.

The chemical action taking place within the lead cell is as follows: On being charged, hydrogen is released at the negative plate and oxygen at the positive plate. The oxygen brings the positive plate to the condition of lead peroxide and the hydrogen reduces the oxide in the negative plate. On discharge both the negative and the positive plates are changed to lead sulphate, and the hydrogen liberated combines with oxygen to form water. The sulphate which is formed is a white substance. Its conductivity is exceedingly poor and if too much is allowed to form at discharge, it may be impossible to recharge the cell. Hence, with the lead cell, care must always be taken not to carry the discharge too far.

There is a large increase in volume when the plates are changed to lead sulphate. This will lead to "buckling" if discharge is carried too far (in other words, if too much of the active material is allowed to change to the sulphate). Buckling will result in loss of the active material from the supporting plates. These supporting plates or grids are always necessary in lead cells, since

neither the spongy lead, nor the lead peroxide have sufficient mechanical strength to stand alone. The supporting grids are usually made of lead or of a lead alloy, so that they will be able to resist the action of the electrolyte.

The voltage of the cell at the end of a charge will vary with the age and condition of the plates and the temperature of the electrolyte. In general it should be about 2.5 volts. At the end of charge, and on open circuit, the voltage will be about 2.05. When discharge is started, the voltage drops to 2 volts or a little less, and thereafter gradually falls during discharge. The voltage should never be allowed to drop below 1.8 volts in a lead cell.

When fully charged, the electrolyte should have a specific gravity of from 1.2 to 1.24. On discharge, the specific gravity should not be allowed to drop below 1.185.

Indications of a complete charge are as follows: The voltage and specific gravity cease to rise; the gassing and boiling of the electrolyte increases materially; the positive plates become a darker brown, and the negative plates become light gray.

There are two classes of lead cells, the "Formed" or Planté, and the "Pasted" or Faure.

In the formed type of plates, the active materials are formed by chemical action, directly upon the lead surfaces of the electrodes themselves. In the pasted plates, the active materials are mechanically applied, in the form of a paste, to surfaces indented and otherwise prepared to hold them. When put into place, the active material hardens.

In general the pasted plate is considered to be the better all-around plate. The formed plates are bulky and more

expensive than the pasted plates, but can stand rougher and more inexperienced use, and will last longer. Formed cells are specially adapted for power house work, while pasted plates are better adapted for vehicle work.

(2) *Nickle-Iron-Alkaline cell (Edison cell)*. In the Edison cell the active materials are of nickel and iron. These are in the form of nickel hydrate which is the active material of the positive plate, and iron oxide, which composes the active material of the negative plate. The electrolyte consists of a 21 per cent solution of potassium hydrate together with a small amount of lithium hydrate.

The chemical principle involved is the oxidation and reduction of the metals in an electrolyte which does not dissolve or combine with the metals or their oxides. When first charged, the positive element, nickel hydrate, is changed to nickel oxide. Thereafter, it never returns to its original form. The iron oxide becomes metallic iron. On discharge, some of the oxygen is taken from the positive nickel oxide, changing it to another oxide of nickel which has less oxygen in it. The negative iron is changed to an iron oxide during discharge. When the cell is again recharged, nickel oxide and metallic iron are again formed. Although the electrolyte, potassium hydrate, enters into the chemical action, it is finally returned to its original state.

The active element of the positive plate, nickel hydrate, is compressed in perforated steel tubes, $4\frac{1}{2}$ inches long and $\frac{3}{16}$ inch in diameter. Within each small tube 315 layers of nickel hydrate are separated by 315 layers of nickel flake. The metallic nickel flake serves as a conductor of electricity between the steel tubes and the

layers of active material. Twenty-one positive tubes are secured on a sub-grid by tongues forced over the flattened ends of the tubes. The sub-grid is made of nickel-plated steel.

The active element of the negative plate, powdered iron oxide, is mixed with a small amount of mercury, and loaded into perforated, nickel-plated, steel pockets. These are flat and are $2\frac{3}{8}$ inches long, $\frac{1}{2}$ inch wide, and $\frac{1}{16}$ inch thick. Sixteen of these pockets are placed in the interstices of a sub-grid, of the same size, shape, and material as the positive sub-grid.

The sub-grids, both positive and negative, are mounted on steel main grids. The number of sub-grids to the main grid depends upon the capacity required. The sub-grids are secured to the main grids by electrical welding. The positive and the negative grids are insulated from each other by means of hard rubber insulating strips, which are attached to the positive grids. In assembling, the negative and the positive grids are fastened by means of properly insulated bolts, so as to form a single structure. They are then placed in the container which holds the electrolyte. This container is of $\frac{1}{8}$ inch thick cold-rolled steel and has welded seams. The plates are insulated from the container by means of hard-rubber pieces.

The voltage of the Edison cell, at the end of charge is about 1.86 volts. On discharge, the voltage falls to about 1.2 volts, and at the end of charge, if the cell is discharging at the normal rate, the voltage drops to 1 volt. The specific gravity of the electrolyte does not change during charge or discharge, remaining at 1.2.

The Edison cell can be left idle, in a fully charged, discharged, or semi-charged, state for an indefinite length of time, without deterioration. It is lighter and smaller than the same capacity lead cell. It is more rugged, and may be subjected to long and repeated overcharge without injury. This cell is especially well adapted for use on shipboard due to the fact that the electrolyte is an alkaline solution, as is sea water. Hence flooding of the battery tank does not give rise to the evolution of dangerous gases as is the case where lead cells become flooded. Edison cells are widely used for train lighting, for electric traction, and for submarine work.

(d) *Capacity of storage cells.* The unit used for storage cells is the "ampere-hour." This is based on the normal rate of discharge, which is usually an 8-hour rate. Thus, a 48 ampere-hour cell will furnish a continuous current of 6 amperes for 8 hours. If a lead cell is discharged in 4 hours instead of 8 hours its capacity will be reduced. That is to say, it cannot furnish 12 amperes in 4 hours, or the same 48 ampere-hour total at the more rapid rate. This is not the case with the Edison cell which can be discharged at any desired rate without decreasing the capacity.

(e) *Uses of storage batteries.* The following table is taken from Foster's "Electrical Engineer's Pocketbook" (D. Van Nostrand):

- (1) For propelling electrically driven motor cars.
- (2) For railway train lighting.
- (3) As a substitute for the ordinary primary battery in telephone and telegraph work.
- (4) To carry the load peak on a supply system.
- (5) To carry the entire load during the periods of light demand, the generating equipment being shut down.

- (6) To regulate the load on systems where the demand fluctuates widely.
- (7) To act as an equalizer on three-wire systems in which the generators are connected across the outsides of the system and give a corresponding voltage.
- (8) To reduce the amount of copper required for systems supplying variable loads.
- (9) To insure continuous service.
- (10) As auxiliaries to exciter dynamos in large alternating-current stations.
- (11) Combinations of any of the above from (4) to (8).

Outline of Lesson 7 — THE ELECTRICAL GENERATOR

- 1. DISTINCTION BETWEEN DYNAMO AND GENERATOR.**
- 2. FUNDAMENTAL PRINCIPLE OF GENERATOR.**
- 3. DIRECTION OF THE INDUCED CURRENT.**
- 4. LENZ'S LAW APPLIED TO THE GENERATOR.**
- 5. ESSENTIALS OF ALL DIRECT-CURRENT GENERATORS:**

(a) Electrical Circuits:

- (1) Armature winding.**
- (2) Field windings.**

(b) Magnetic circuit:

- (1) Field frame or Yoke.**
- (2) Pole pieces and pole shoes.**
- (3) Air-gap.**
- (4) Armature core.**

(c) Commutator and Brushes.

6. CONSTRUCTION OF GENERATOR:

(a) Stationary parts:

- (1) Field frame or yoke.**
- (2) Pole pieces.**
- (3) Pole shoes.**
- (4) Field windings.**
- (5) Brushes.**
- (6) Brush holder.**
- (7) Brush rigging.**
- (8) Brush bus.**
- (9) End bells and bearings.**

(b) Rotating parts:

- (1) Armature core.**
- (2) Armature winding:**
 - Lap winding.**
 - Wave winding.**
- (3) Commutator.**
- (4) Shaft.**
- (5) Oiling rings.**

(c) Air-gap.

7. ACTION OF COMMUTATOR.

8. USE OF MULTI-COILS.

9. GENERATOR EXCITATION:

- (a) Separate excitation.
- (b) Self-excited generator:
 - (1) Shunt generator.
 - (2) Series generator.
 - (3) Compound generator:
 - Short shunt.
 - Long shunt.

10. GENERATOR CHARACTERISTICS:

- (a) Separately Excited:
 - (1) No-load characteristic.
 - (2) Speed characteristic.
 - (3) Load characteristic.
- (b) Shunt:
 - (1) No load characteristic.
 - (2) Speed characteristic.
 - (3) Load characteristic.
- (c) Series:
 - (1) Magnetization curve.
 - (2) Load characteristic.
- (d) Compound:
 - (1) Cumulative:
 - Flat Compounded.
 - Over-compounded.
 - (2) Differentially compounded Generator.

11. VOLTAGE REGULATION OF GENERATOR.

12. LOSSES IN GENERATOR:

- (a) Stray Power Losses:
 - (1) Iron or Core Loss:
 - Eddy Current losses.
 - Hysteresis.
 - (2) Friction or Mechanical Losses:
 - Bearing friction.
 - Brush friction.
 - Windage.
- (b) Copper Losses:
 - (1) Loss in armature winding.
 - (2) Loss in field winding.
 - (3) Losses in other windings.

13. EFFICIENCY OF GENERATOR:

- (a) Definition.
- (b) How Determined:
 - (1) Directly.
 - (2) Indirectly.

14. ARMATURE REACTION:

- (a) Definition.
- (b) Neutral plane.
- (c) Illustration of action by use of Vectors. Effects of Brush Shifting.
- (d) Effects of Armature Reaction shown by Flux Diagram.
- (e) Methods of Reducing Armature Reaction:
 - (1) Compensating coils.
 - (2) Reduction of armature flux by reluctance in its path.
 - (3) Use of saturated pole tips.
 - (4) Eccentric pole shoes.

15. COMMUTATION:

- (a) Conditions for Sparkless Commutation.
- (b) Electrical Causes of Sparking:
 - (1) Armature Reaction.
 - (2) Self-induction.
- (c) Sparkless Commutation by Shifting Brushes.
- (d) Sparkless Commutation by Use of Interpoles:
 - (1) Definition of Interpole.
 - (2) How connected.
 - (3) Action of Interpole.
- (e) Resistance Commutation.

16. CAPACITY OF GENERATORS:

- (a) Size of armature windings.
- (b) Commutation.
- (c) Ventilation.
- (d) Excessive voltage drop.

17. THREE-WIRE GENERATOR:

- (a) Principle of Operation.
- (b) Advantages of three-wire system over two-wire system:
 - (1) Saving in copper.
 - (2) Two voltages available.
- (c) Allowable unbalancing.

18. GENERATOR OPERATION:

- (a) Measuring instruments necessary.
- (b) Protective devices.
- (c) Shunt Generator Operation:
 - (1) Starting.
 - (2) Stopping.
 - (3) Shunt Generators in Parallel.
- (d) Compound Generators:
 - (1) Starting and stopping.
 - (2) Requirements for parallel operation.
 - (3) Action of equalizer.
 - (4) Throwing compound generator in parallel with another.
 - (5) Cutting out compound generator which is in parallel with another.

19. GENERATOR TROUBLES:

- (a) Failure to build up:
 - (1) Loss of residual magnetism.
 - (2) Reversed field.
 - (3) Ground in field winding.
 - (4) Open circuit in field or armature.
 - (5) Brushes not correctly located.
- (b) Failure to carry load:
 - (1) Series field reversed.
 - (2) Broken connection.
- (c) Excessive sparking:
 - (1) Electrical causes.
 - (2) Mechanical causes.
- (d) Excessive heating:
 - (1) Commutator and brushes.
 - (2) Armature.
 - (3) Field windings.
 - (4) Bearings.

20. GENERATOR TESTS:

- (a) Short-circuit:
 - (1) Armature winding — Bar-to-Bar test.
 - (2) Field winding.
- (b) Ground:
 - (1) Armature winding.
 - (2) Field winding.
- (c) Open circuit:
 - (1) Armature winding.
 - (2) Field winding.

LESSON 7 — THE ELECTRICAL GENERATOR

1. Distinction between Dynamo and Generator

A dynamo is a machine for converting mechanical energy into electrical energy or vice versa. A generator is a machine for converting mechanical energy into electrical energy.

2. Fundamental Principle of Generator

If a conductor cuts lines of force, an e.m.f. will be induced in it. If the conductor forms a closed electrical circuit, a current will flow. As explained above, under "Electromagnetic Laws," the value of the induced e.m.f. will depend upon the strength of the magnetic field, upon the length of the conductor, the speed of cutting and the relative direction of the field and the conductor.

3. Direction of the Induced Current

The direction of the induced current depends upon the direction of the magnetic field and the direction in which the conductor cuts the field. The relationship existing can be remembered by means of the right-hand rule explained above.

4. Lenz's Law Applied to the Generator

The more the current drawn from a generator, the harder it is to turn it. According to Lenz's Law, as stated above, whenever an e.m.f. is induced by cutting of lines of force and current flows, the magnetic field due to this current will react upon the original field in such a manner as to

tend to stop the motion. (Fig. 4.) This explains why it is harder to turn the generator when current is flowing, than when the external circuit is open. In the former case, the magnetic field due to the current flow reacts upon the exciting field in such a way as to tend to prevent rotation and this reaction becomes greater and greater as more current is drawn from the generator, since greater current also means an increased magnetic field due to the current.

5. Essentials of all Direct-Current Generators

(a) *Electrical circuits:*

(1) *Armature winding.* Conductors which cut flux.

(2) *Field windings.* These furnish the electrical means of obtaining the magnetic field.

(b) *Magnetic circuit.* (Purpose of these parts will be explained in paragraph on construction.)

(1) Field Frame or Yoke.

(2) Pole Pieces and Pole Shoes.

(3) Air-Gap.

(4) Armature Core.

(c) *Commutator and Brushes.*

6. Construction of Generator

(a) *Stationary parts:*

(1) *Field frame or Yoke.* This acts as a supporting frame for the entire machine, in addition to being a part of the magnetic circuit. The field frame may be of cast iron or of cast steel. The cast-iron frame is cheaper in first cost, but the use of cast steel will result in a lighter and more efficient machine, since the permeability of cast steel is higher than cast iron and hence less material will

be necessary and also less ampere-turns in order to get the same magnetic field strength. In modern generators, a circular frame is used. In small machines, the frame is made in one piece, while in large generators, it is usually made in two pieces, which are bolted together. This allows the upper part to be lifted off, thus facilitating the removal of the armature.

(2) *Pole pieces.* These support the field windings and form a part of the magnetic path. They are sometimes cast in one piece with the field frame, in which case they may be of cast iron or of cast steel. In most cases, however, they are made separately of wrought iron or soft steel, and are bolted or welded to the field frame. They are often referred to as *Magnet Cores*. They are made solid in some cases, while in others they are made of thin punchings or laminations, which are insulated from each other by means of japan, varnish, shellac, or simply rust. Small machines are sometimes made with two poles (Bipolar) but all others have a number of poles (Multipolar). The use of multipoles results in a lighter machine, and incidentally there is a saving of field copper and a reduction in sparking. If there are too many poles, however, there will be excessive leakage flux between the poles.

(3) *Pole shoes.* These are sometimes called pole pieces, but should not be confused with the core itself. The shoes flare out beyond the pole, and thus give a uniformly distributed magnetic field. They are usually a part of the magnet core, although they may be made separately and bolted to the core. Eddy currents are often induced in the face of the shoes by the rotation of the slotted armature core. These currents result from the variation

in flux density as first the tooth and then the slot pass under the shoe. Laminating the pole shoes reduces these eddy currents.

(4) *Field windings*. An exciting current, passing through the field windings or field coils, furnishes the necessary magnetic field. The field coils are connected in series and are wound in such a way that adjacent poles will be of opposite polarity. The coils are made of copper and are rectangular in shape. For low current values they are made of wire, while for heavy currents they are of ribbon, straps or bars. The field windings are usually held in place by the pole shoes, although in some cases special supports are provided. Shunt coils (par. 9 (b) (1)) are usually made of insulated copper wire, wound on insulated shells, and then taped and saturated with insulating compound. Series coils (par. 9 (b) (2)) are generally made of bare copper strap and the turns, which are edge wound, have air spaces between them and are separated by asbestos ribbon. In some cases the series coils are wound on top of the shunt coils, with suitable ventilation spaces between; in other cases they are separated from each other, thus giving better ventilation. Ventilation spaces are usually provided between the coils and the magnet core. Proper ventilation and means of heat dissipation are essential if low temperatures are to be maintained. Interpole windings carry the same currents as series windings and are usually made and wound like them.

(5) *Brushes*. The brushes rest on the rotating commutator and collect the current from it. They are made of compressed powdered coke and graphite. The graphite

aids the lubrication. The brushes can be obtained with varying degrees of hardness to suit conditions. In special generators, such as the low-voltage, high-current machines used for electro-plating, copper gauze or copper leaf brushes are used. In medium size and larger generators the brushes are placed side by side, in sets. This method of construction not only provides the necessary cross-sectional contact area for carrying the current (about 40 amperes per square inch) but it also gives greater flexibility than a single brush could give, more even wear on the commutator, and greater ease of repair. Brushes are usually set at a small angle to the commutator which in most cases rotates in the same direction as the slant of the brush. In the case of railway motors, the brushes are set radially. By widening the brush, the time of commutation can be increased, but the width is limited due to the fact that too wide a brush will short-circuit too many armature coils and will result in a high e.m.f. of self-induction and increased sparking. A small braided flexible copper conductor, called a "pig-tail" connects the brush, electrically, to the brush holder. When the pig-tail is soldered to the brush, the upper half is copper-plated. Sometimes the pig-tail is bolted to the brush. It is usually bolted to the brush holder.

(6) *Brush holder.* In some types of holder, the brush is free to move up and down in a sort of a box arrangement and an adjustable spring holds it down on the commutator with a fixed pressure. This is usually about 1.5 pounds per square inch of contact area. In some cases spiral springs are used, while in others the springs are flat. In certain brush holders, the brush is clamped

rigidly to a support which is itself pivoted. There are various other types of brush holders. In general the brush which is free to move up and down is preferable, especially for high-speed machines.

(7) *Brush rigging.* This includes the brush studs, which carry the brush holders, the brush yoke and other apparatus used for shifting the brushes. The brush yoke carries the brush studs on it, but it is suitably insulated from them. In general, it consists of two rings connected by radial cross arms, with the larger diameter ring fitted accurately into a groove in the field frame and with means provided for shifting all the brushes at once, if so desired. The brush yoke is usually moved, in large machines, by turning a large handwheel, which operates through gearing. Of course, in modern interpole generators, it is not necessary to shift the brushes and in this case, the shifting device may be omitted.

(8) *Brush bus.* Two heavy rings of copper, called brush buses, carry the load current, and all the positive brush studs are connected to one, while all the negative studs are connected to the other. Flexible cables are soldered to the brush buses and these lead to a terminal board which is fastened to the field frame.

(9) *End bells and bearings.* In small generators, end bells, or as they are sometimes called, *end frames*, are bolted to the field frame and these carry the bearings. On larger generators, the bearings are usually placed in separate pedestals. Sometimes only the bearing pedestal on the commutator side is made separate, while the other pedestal is cast in one piece with the field frame. In large machines, the field frame and the bearing pedestals are

usually firmly bolted to a cast-iron bed-plate. The bolts pass through lugs cast on the sides of the field frame.

(b) *Rotating parts:*

(1) *Armature core.* The *drum* type armature core is the modern commercial type. In this armature, the windings all lie on the outside face of the core. In the older ring type of core, the windings were partly on the outside face of the core, and partly within the ring. Thus, one-half the windings served no useful purpose, since the windings inside the ring cut no flux, and moreover there was doubled copper loss in the armature.

The older armatures were of the *smooth core type*. That is to say, the conductors were laid on the smooth face of the core and held in place with binding wires. Practically all modern generators, with the exception of certain special machines, are now made with *slotted armature cores*. The conductors are laid in the slots, thus being protected from injury, and they are also thus held more securely in place. Slotting the armature core resulted in reduced air-gap and hence lower reluctance in the magnetic circuit.

There are three types of slots; open, semi-enclosed, and closed. The first two are the only ones used in d.c. work, the open slot being the one most commonly employed. The open slot is easy to wind and form-wound coils can be used. It has an added advantage of giving a lower e.m.f. of self-induction in the short-circuited coils, than the semi-enclosed slot. However, it has a greater magnetic reluctance than the semi-enclosed slot, and it does not protect the windings as well.

The armature core is always *laminated*, at right angles

to the shaft, in order to reduce the eddy-current loss. Since it serves to form a part of the magnetic circuit, as well as to hold the conductors in place, it must be made of wrought iron or of soft electrical steel.

Radial ducts are provided in the armature core for the purpose of ventilation. Steel *spacing pieces* hold the laminations apart to form these ducts. The rotation of the armature aids the ventilation, since it forces the air up through the ventilating ducts and thence through the overhanging ends of the armature coils.

In small armatures, the laminations are punched in one piece, and are keyed directly to the shaft. End flanges and bolts are used to hold the laminations in place. In large armatures, the core consists of built-up segments, carried on an iron *spider*. The spider consists of spokes, to which the armature segments are attached, and a hub, which is pressed and keyed onto the shaft. This method of construction results in a saving of material, and a lighter machine.

(2) *Armature winding*. An e.m.f. is induced in the armature winding, when it cuts lines of force. In small generators the armature windings are made of copper wire, while in machines having a large current output, copper bars are usually used. In practically all direct-current armatures, the windings form a closed circuit. A number of separate interchangeable coils are connected together to form a continuous winding. Each coil consists of several turns of conductor, insulated separately by means of insulated linen tape, compound, or varnished cloth or paper. The coil itself is wrapped with several layers of insulating tape, and is then impregnated

with damp-proof varnish. The slots are lined with mica, fiber, or other insulating material, before the coils are placed in them. The ends of the armature core are also insulated so that the coils cannot ground there. In small generators the armature coils are usually placed in open slots and are secured by means of "binding" or "banding" wires, which are wound around the core. These wires are of tinned steel, phosphor bronze, or brass. They are insulated from the armature core, and usually the laminations are grooved for them, so that the finished armature will have an even surface. In large machines the conductors are held in place by wedges. These are usually of fiber or wood, although brass wedges are sometimes used. The wedges are driven into the top of the slot.

The leads which are brought out from the armature coils are soldered into a neck in the lugs of the commutator bars. There are two methods of connecting up the windings to the commutator bars. In one method, the armature is said to be *Lap wound* (sometimes called "parallel" or "multiple" wound). In the other method, the armature is called *Wave wound* (also called "two-circuit" or "series" wound).

In the elementary form of *lap* winding, the method of connection to commutator bars is as follows: One side of a coil is connected to a commutator bar, and the other side of the coil, which is located 180 electrical degrees¹ away, approximately, has its end connection brought back (whence the name lap) and soldered to the next

¹ NOTE.—The distance from the center of a north pole to the center of the adjacent south pole constitutes 180 electrical degrees.

adjacent commutator bar. This method of overlapping the ends is continued all the way around the armature, until all the slots have been filled, and the circuit has closed on itself. The coils must all be symmetrical. This means that if there is a forward throw of a certain number of slots on the first coil, all the other coils must have the same forward throw. In like manner all the return throws must be the same. In the lap-wound generator, there are as many paths for the current as there are poles. Hence the name parallel or multiple winding. This necessitates the use of as many sets of brushes as there are poles. An increased number of paths in parallel means increased current capacity.

In a *wave* winding, the two sides of a coil are located 180 electrical degrees apart, as in the lap winding, but instead of having the second side of the coil connect to an adjacent commutator segment, as in the lap winding, it connects to a commutator bar located 360 electrical degrees from the first bar. In this winding there are only two paths for the current, all the coils in each path being in series, whence the name *series* winding. For this reason only two sets of brushes are necessary, although in larger machines, as many sets of brushes as there are poles are often provided, since this gives greater brush area and better commutation. The name wave winding is derived from the appearance of the end leads, which progress around the armature in a sort of a wave form. Since there are more coils in series in a wave winding than in a lap winding, the wave winding gives a higher voltage.

In the case of two identical four-pole machines, the

one lap wound and the other wave wound, the lap-wound machine will give only one-half the voltage of the wave wound, but it will have double the current-carrying capacity. Of course the output of the two machines will be identical. For small direct-current machines, the wave winding is cheaper and is more often used. Figures 37 and 38 show a way in which it is often possible to tell a wave-wound armature from a lap-wound one.

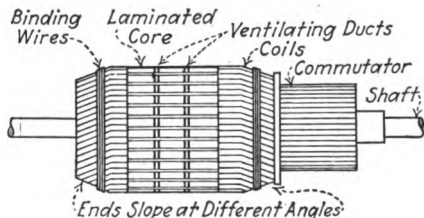


FIG. 37. — Lap-wound armature showing ends sloping at different angles.

(3) *Commutator.*

This is in reality an external reversing switch. It changes the connections of the armature coils with the line, every time the current reverses in the coils and in this way the current on the line is always kept in one direction. The action of the commutator will be

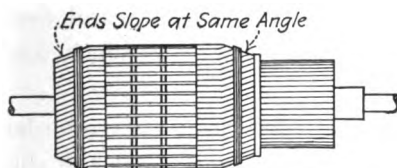


FIG. 38. — Wave-wound armature showing ends sloping at same angle.

explained in greater detail in paragraph 7. The commutator is made up of hard-drawn copper bars, insulated from each other and from the steel bushing on which they are

assembled, by means of molded mica segments. In smaller commutators, a slotted neck is provided, in one piece with the bar, for fastening the armature leads. In the larger sizes, this neck is brazed to the bar. *Wedge Rings* fit into the "V" shaped grooves cut in the bottom

of the commutator bars and these are clamped tightly in place by means of *Clamping Rings* or *Clamping Bolts*. In some cases, the commutator is carried on an extension of the armature spider, while in others it is mounted on the armature shaft. The steel bushing, on which the bars are assembled, is pressed on the machined seat provided for it on the spider or shaft. The commutator is the weakest part of the generator, both electrically and mechanically. The majority of generator troubles take place at this point and these will be explained in detail in a later paragraph.

(4) *Shaft*. The shaft is usually made of forged steel accurately machined to size. Where the spider construction is used, the hub of the spider is pressed or shrunk on the shaft and in addition is keyed on.

(5) *Oiling rings*. These are for the purpose of automatically feeding oil up into the bearings. The rings rest loosely on the shaft. One ring is provided for each bearing. The rotation of the shaft causes the rings to rotate. The lower ends of the rings dip into oil wells and thus oil is constantly being carried up onto the shaft and bearings.

(c) *Air-gap*. The air-gap is mechanically necessary in order to give clearance between the rotating parts and the stationary parts of the generator. Of course, a stiff magnetic field is necessary to give satisfactory generator operation.

7. Action of Commutator

The commutator acts as a mechanical rectifying device. There is alternating current in the armature coils, since when the conductor cuts flux under a north pole, the in-

duced e.m.f. acts in one direction, while when the conductor cuts flux under the south pole, the e.m.f. acts in the reverse direction. However, when the current is taken off the commutator by the brushes, the current is direct, or uni-directional. The way in which the commutator delivers direct current to the line can best be explained by using a two-segment commutator and single-coil armature, as an example. Such a generator could not be used commercially, but for the purpose of explaining the fundamental principles it is simpler and clearer than a multi-segment commutator. The action, however, is exactly the same, whether

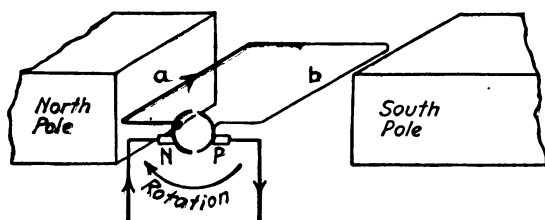


FIG. 39.—Action of commutator illustrated by two-segment commutator. Coil *a* is shown cutting upwards through the magnetic field.

there are few or many commutator bars. In the diagrams, one side of the coil, *a*, and one of the commutator segments, are shown in heavy lines, while the other side of the coil, *b*, and the other segment, are drawn with light lines. In Fig. 39, *a* is cutting upwards through the magnetic field and *b* is cutting downwards (clockwise rotation). Consequently, according to the right-hand rule, the current is flowing away from the brush in *a* and towards the brush in *b*. Figure 40 shows the same coil after it has turned half a revolution. The heavy side *a* is now cutting down through the field and hence the current in it is flowing towards the

brush instead of away. In like manner, *b* is now cutting upwards through the flux, and hence the current is flowing away from the brush instead of towards it. In other words, as the sides of the coil have passed from one pole to the next, the current direction has reversed in them. However, the commutator segments have revolved with the coil, and the heavy line segment, which was touching brush *N*, in Fig. 39, is touching brush *P* in Fig. 40. Thus the commutator has reversed the connection from the negative brush to the positive brush, as the current in coil side *a* has changed from

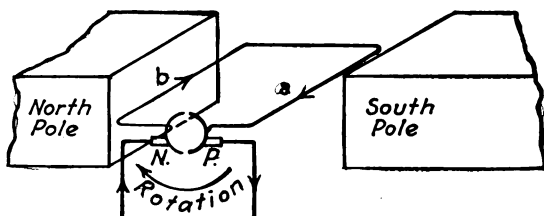


FIG. 40. — Illustration of action of commutator. Coil *a* has now passed through half a revolution and is shown cutting down through the field. Note that heavy commutator segment in this case touches positive brush.

negative to positive direction. By this means, positive direction current is always kept connected to the positive brush.

8. Use of Multi-coils

In the single coil described in paragraph 7, the current obtained would be direct, but it would not be continuous. The reason for this is as follows: When the coil is cutting lines of force at right angles, the maximum e.m.f. is induced. As the coil rotates, the angle of cutting becomes less and less and the induced voltage becomes correspondingly smaller until finally when the coil moves parallel to the lines of force and cuts no flux, the e.m.f. becomes zero. Thus

it can be seen, that although the current in *a*, Fig. 39, is a maximum in one direction and in the next figure has attained a maximum in the reverse direction, nevertheless, the current had gradually decreasing values until it reached zero, when *a* was halfway between the poles and then gradually increasing values until it reached the position shown in Fig. 40. The e.m.f. is induced in pulses or waves and the action of the commutator in no way remedies this. The commutator simply serves to send all these waves out on the line in the same direction, but nevertheless the current is continually passing through a series of values from zero to maximum and back to zero again. If an electric lamp were connected in such a circuit, it would become bright for an instant, then would dim down, and would continually flicker in this manner. In the same way, it would be impracticable to operate any electrical apparatus with such a current. The remedy for this trouble lies in the use of multi or many armature coils. The use of multi-coils has the effect of smoothing out the pulses of current into one continuous current. This is accomplished, due to the fact that although several coils may not be cutting any flux, still a large number will be cutting flux and there will always be some coils cutting lines of force at right angles. These coils are all connected in series to form a closed circuit (see par. 6 (b) (2)) and thus a higher voltage is obtained in addition to a steady direct current.

9. Generator Excitation

(a) *Separate excitation.* In the separately excited generator, the current for producing the magnetic field is obtained from some source external to the generator itself. This source is

either another generator or else a storage battery. This type of excitation is mainly used in special generators such as those used for battery charging, electroplating and testing.

(b) *Self-excited.* Generators which depend on their own current for their field excitation must "build up" their magnetic field and hence their voltage, gradually. In order to build up, they depend upon the *Residual Magnetism* present in the iron of the poles, in order to get a start. When the armature first cuts the residual field, a small e.m.f. is induced and this sends a small current through the field windings. This increases the field strength by a small amount, with the result that a slightly larger e.m.f. is induced, and hence more current is sent through the field windings. This process of "building up" continues until the full voltage is attained. If the field connections should be reversed, the small current flowing through the field windings would give a magnetic field tending to kill the residual magnetism and hence the generator would not build up. Even if this current in the field windings were sufficient to reverse the original polarity, the machine would not build up, for in that case, the current in the armature windings would also reverse (since there is a fixed relation between polarity and direction of rotation) with the result that the field current would again give a magnetic field tending to oppose the new polarity. Hence, with a given direction of rotation, the field connection must be made so that the current will flow in a certain direction only. If the residual magnetism should be reversed, through any cause, the machine would then build up in the reverse direction.

The e.m.f. attained by any generator increases directly

with increase in field strength, increase in number of useful conductors in series, and increase in speed.

There are three classes of self-excited generators:

(1) *Shunt generator*. In this type (Fig. 41) the field winding is shunted across the armature terminals. Voltage control is usually effected

by means of a regulating resistance (rheostat) placed in series with the shunt field. The resistance of the shunt winding is made such, that only a small percentage of the load current flows through it.

Consequently, this

winding can be of comparatively fine size wire, but a large number of turns are necessary to get the required ampere-turns.

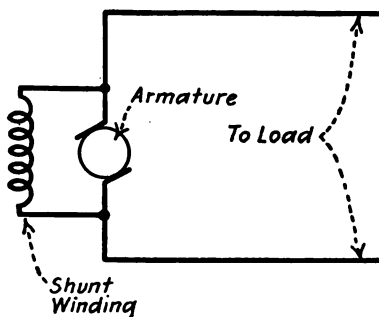


FIG. 41. — Elementary diagram of a shunt generator.

(2) *Series generator*. In this type, the exciting winding is connected in series with the armature and the load (Fig. 42) and in consequence it carries the full-load current and must therefore be made of large size wire. At the present time, the series generator has no commercial importance but its characteristics are explained, since a clear understanding of them will aid in understanding the action of the compound generator. The series generator was formerly used extensively as a constant-current machine for arc lighting.

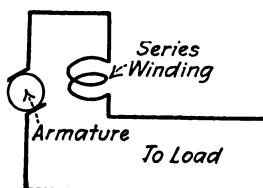


FIG. 42. — Elementary diagram of a series generator.

It was necessary to practically short-circuit the machine in order to get it to build up and a special device was provided for this purpose. The voltage was regulated by

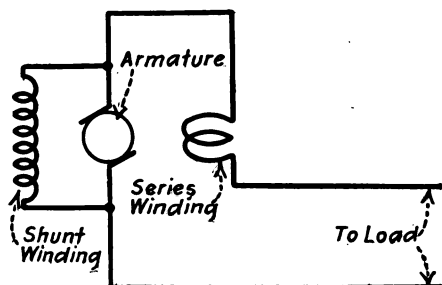


FIG. 43. — Elementary diagram of a short-shunt compound-wound generator.

means of a resistance shunted across a part of the field. The generator supplied current to a number of lamps in series and when one lamp was cut out and the resistance of the external circuit thus lowered, increased cur-

rent tended to flow. This operated a solenoid in series in the circuit which thus moved the rheostat arm in such a direction as to decrease its resistance, in this manner shunting more of the current away from the series field, and preventing a rise of e.m.f.

(3) Compound generator.

The compound generator has both a shunt winding and a series winding. These may be connected either "short shunt" as in Fig. 43, or "long shunt" (Fig. 44). There is practically no electrical

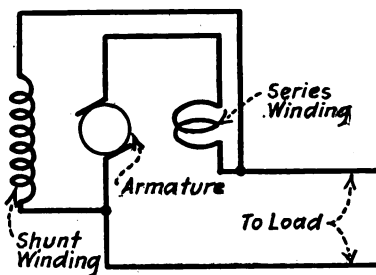


FIG. 44. — Elementary diagram of a long-shunt compound-wound generator.

difference between these two methods of connection. The short shunt has a slightly higher voltage across the shunt field, since in the long shunt there is a small voltage drop across the series winding. The shunt winding consists

of many turns of fine wire, while the series winding consists of a few turns of heavy wire.

10. Generator Characteristics

(a) *Separately Excited.* The separately excited generator is of especial value for use where a reversed magnetic field would be extremely undesirable.

(1) *No-load characteristic.* This is obtained by running

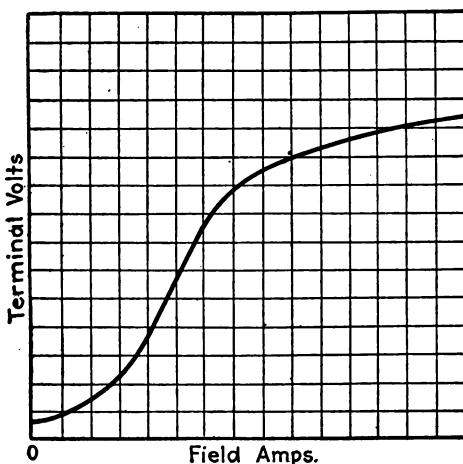


FIG. 45. — No-load characteristic of separately excited generator.

the generator at constant rated speed and no load, and varying the field current from zero to a maximum value, and taking readings of the terminal voltage. If these voltage readings are plotted against the corresponding, values of field current, a curve such as shown in Fig. 45 will be obtained. In order to have zero voltage at the start, with zero field current, it is necessary to “kill” the residual magnetism by flashing current through the

field winding in the wrong direction for just an instant. The curve obtained shows the relation between the magnetizing current and the resulting flux and corresponds to a *Magnetization Curve* of the iron in the poles. It will be noted that there is a rapid increase in voltage (corresponding to similar increase in flux) at first. As the exciting current is increased more and more, the increase in voltage is not proportionally as great and finally a point is reached where, no matter how much the excitation is increased, there will be *no* rise in voltage. This illustrates the "*Saturation*" of the magnetic circuit, which will not permit the crowding in of more than a certain number of lines of force. This number, of course, depends on the material forming the magnetic path. If the field excitation is reduced, and the terminal voltage again read and plotted as before, it will be found that this curve lies higher than the first. This is due to the hysteresis of the iron. The iron apparently offers a certain resistance to having its magnetism changed. When the zero value of field current is again reached, there will be a small e.m.f., due to the residual magnetism.

(2) *Speed characteristic.* If the generator is run at no load and readings are taken of the terminal e.m.f. at various speeds, it will be found that the voltage increases directly with the speed, so long as the flux is kept constant.

(3) *Load characteristic.* Fig. 46. This is obtained by running the generator at constant speed. The field excitation is adjusted to give rated voltage at no load, and the field current is then kept constant at that value. The load is then varied from no load to about 150 per cent overload. Simultaneous readings are taken of armature

current and terminal voltage and these are plotted as shown in Fig. 46. The curve shows that there is a gradual decrease in terminal voltage, as the load increases. This is partly due to increased voltage drop in the armature winding as the current increases, and partly to the increase of armature reaction, which tends to weaken the field. (See par. 14.)

(b) *Shunt:*

(1) *No-load characteristic.* This is obtained in the same

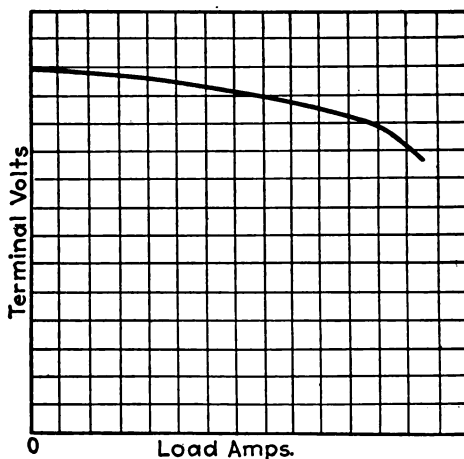


FIG. 46. — Load characteristic of separately excited generator.

way as in the case of the separately excited generator. The curve obtained is practically the same as for separate excitation and can be taken as the magnetization curve of the machine. There will be a slightly lower voltage due to the voltage drop resulting from the small current used in the field winding. This will be negligible, however. The no-load curve consists of three distinct parts: the lower part, which is straight, the middle part, or knee,

and the upper part which is practically a straight line. In commercial generators, it is usual to excite the field above the bend in the no-load curve in order to get a more stable condition as regards voltage. A generator which is operated at an excitation above the "knee" of the curve, will not show great change in voltage if there is a slight change in exciting current. The reverse

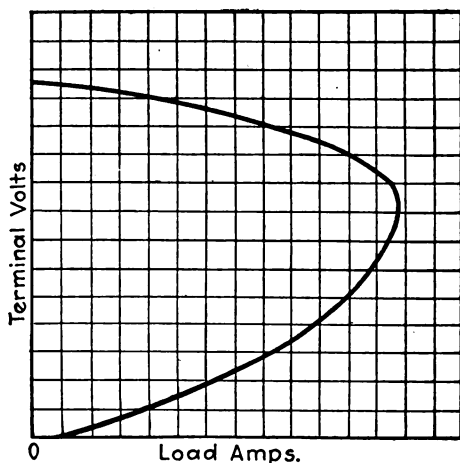


FIG. 46 (a). — Load characteristic curve of a shunt generator.

is true in the case of a generator operated at an excitation below the "knee."

- (2) *Speed characteristic.* This is determined in the same manner as for the separately excited generator and the same results are obtained.
- (3) *Load characteristic,* Figure 46 (a). The method of obtaining this characteristic is the same as for the separately excited generator. It will be found that the voltage drops with increase of load, but the drop is greater in the case of the shunt than in the case of the separately ex-

cited generator. There are three reasons for the voltage drop with increased load. These will be explained in detail. An increase of load, when referring to a generator, means a reduction of the resistance of the external circuit.

The voltage induced in the armature winding of a generator is higher than that at the terminals. This is due to the fact that the armature winding has resistance. The brushes, brush contacts, leads, and other parts of the internal circuit have resistance also. Wherever there is resistance, there will be voltage drop, if current flows. In accordance with Ohm's Law, this voltage drop will increase with increase of current. Hence, when load increases on a generator (that is, when the resistance of the external circuit is reduced), more current will flow from the armature winding. This will then result in an increased voltage drop in the internal circuit of the generator. From this it can be seen that even if the voltage induced in the armature winding should remain the same with increased load, still the terminal voltage would drop lower and lower, due to the increased drop as the current increased.

Armature reaction increases with increased load and the result of this is a weakening of the magnetic field. (See paragraph 14.) This in turn results in a lower induced voltage in the armature windings, and consequently a lower terminal voltage.

The above causes of voltage drop in a shunt generator with increased load, together combine to effect a third cause of voltage drop. Since the shunt winding is shunted across the generator terminals, the amount of current flowing through it will depend upon its resistance (or to

be more exact, the resistance of the shunt circuit) and upon the voltage applied to it. If the resistance is left unchanged, and there is a drop in voltage, there will be a corresponding drop in current. This is exactly what happens when the terminal voltage of the generator falls, due to the two reasons mentioned above. When this occurs, and the exciting current is reduced, there will be a still further reduction of the strength of the magnetic field. This will again mean lower induced voltage in the armature winding and hence lower terminal voltage.

If the load is gradually increased, and the windings are large enough to carry the overload without undue heating, a point will be reached where the current flowing from the generator will become less, instead of greater, as the resistance of the external circuit is reduced. This is caused by the fact that at this point the three causes of voltage drop mentioned above, result in a lowering of the terminal voltage at a proportionately greater rate than the reduction of resistance in the external circuit. After this point has been reached, still further reduction in the external circuit resistance results in rapidly increased voltage drop accompanied by decreasing current. Finally, when a dead short-circuit is placed across the generator, the voltage drops to zero. It should not be inferred from this that it is safe to short-circuit every shunt generator in this manner. In the larger machines, it is probable that the current-carrying capacity of the armature conductors will be exceeded before the point of current decrease is reached.

(c) *Series Generator:*

(1) *Magnetization curve.* In order to obtain the mag-

netization characteristic of a series generator, it is necessary to separately excite the field. The test is then run in the same way as in the case of the separately excited generator, and with practically the same results.

(2) *Load characteristic* (Fig. 47). As stated above, it is necessary to reduce the external resistance of a series generator to a very low value in order to get it to build up. The value of the external resistance at which the

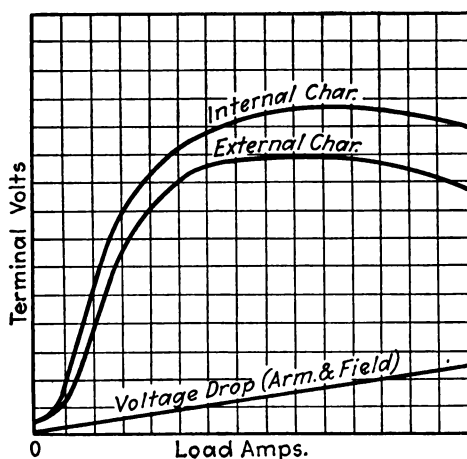


FIG. 47. — Characteristic curves of a series generator.

generator starts to build up is sometimes called the “critical” resistance. It will be noticed that the load characteristic or “external characteristic” curve of a series generator resembles the magnetization curve. It does not reach as high a voltage however, since there is a voltage drop due to the resistance of armature and field and also due to armature reaction. The current which flows from the armature must also flow through the field winding, which is in series with the armature and

the load. At first, the increase of voltage with increased load is very rapid, but as saturation of the magnetic circuit is reached, the voltage no longer rises, even though the exciting current and the load increase. Finally, with increased load, the voltage drops excessively, due mainly to greatly increased armature reaction, but also to increased drop in armature and field winding. If the resistance of the armature and the field be measured and multiplied by the current for various values of load, a straight line can be plotted to the same scale as the load characteristic curve and this will represent the armature and field drop. By adding these values to the "external characteristic" curve, a curve called the "internal" characteristic curve of the series generator is obtained. The difference between this curve and the magnetization curve will show the voltage drop due to armature reaction.

(d) *Compound Generator:*

(1) *Cumulative.* The cumulative compound generator is far more important commercially than either the shunt or the series generators. Since the series generator shows an increasing voltage with load, and the shunt generator a slightly falling voltage with increased load, the two are combined in the compound generator to give a fairly constant voltage under varying conditions of load. In the cumulatively compounded generator, the series and shunt fields are wound to aid each other. That is to say, if the shunt winding tends to make a pole a north pole, the series winding will also be wound in such a direction to give north polarity. The number of turns in the series winding will determine the degree of compounding. The

entire load current does not flow through the series winding, but a portion is always shunted through a resistance called a "*series shunt.*" This may be variable, although it is usually a fixed resistance. It usually consists of german silver or iron grids, located on the frame of the machine. The necessary amount of this resistance is usually adjusted at the factory. With a high-resistance series shunt, most of the current will flow through the

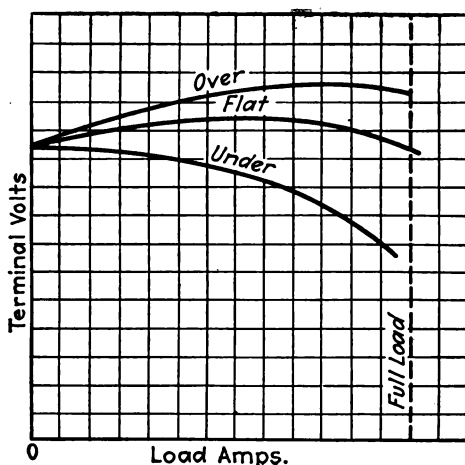


FIG. 48. — Load characteristic curves of cumulatively compounded generators.

series field and a rise in voltage will follow an increase of load. By reducing the resistance of the series shunt, more current will flow through it, and hence less through the series winding. Hence the amount of compounding will be less and by proper adjustment, the voltage at full load may be made the same as at no load.

A generator which has the same voltage at full load as at no load, is said to be "Flat Compounded" (Fig. 48).

It is impossible to keep the voltage absolutely constant through all values of load current and there is usually a slight rise in voltage for intermediate loads between no load and full load. This is due to the fact that the flux does not increase in exactly the same ratio with the increase of exciting current. In some generators, it is possible to have a voltage drop at intermediate loads. The flat compounded generator should be used in cases where the load is located near the generator. In this case, the voltage drop in the line is negligible and so the voltage at the load will be practically constant.

An "Over-Compounded" generator is one which has a higher voltage at full load than at no load. The amount of over-compounding should be sufficient to take care of the voltage drop in the line. This generator is used where the load is at a distance from the machine and there is a considerable voltage drop in the line. This voltage drop increases as the load increases, but if the machine is over-compounded to the proper degree, the voltage at the terminals of the generator will rise with increased load, while the voltage at the end of the line (at the load) will remain nearly constant. This type of generator is the most common type of compound generator. It is possible to have too few turns on the series winding, and thus to have a generator, which shows a drop in voltage with increasing load. Such an "under-compounded" machine would have no advantage over a shunt generator and so it is not used.

(2) *Differentially-compounded Generator* (Fig. 48 (a)). In this type, the series winding opposes the shunt winding. Thus if the shunt winding tends to produce north po-

larity, the series winding would tend to kill the field and produce south polarity. This generator is not of great commercial importance since it is only used for special purposes. It is used in automobiles for charging batteries. In this case, if the speed becomes excessive, there is a momentary increase of current, but this current in flowing through the series winding weakens the magnetic

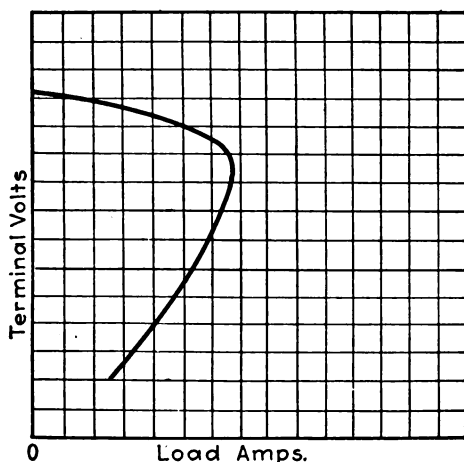


FIG. 48 (a).— Load characteristic curve of a differentially compounded generator.

field to such an extent that there is a great reduction in voltage and hence in the current. In this way, it is possible to prevent the batteries from being charged at too rapid a rate. If a generator is run at constant speed and shows full voltage at no load but shows a great drop in voltage as soon as an attempt is made to put a load on it, this is a pretty sure sign that it is differentially compounded.

11. Voltage Regulation of Generator

This refers to the change in terminal voltage occurring between zero load and full rated load and at temperature attained under normal operation. Regulation is usually expressed as a percentage. Thus "percentage voltage regulation" is the difference between no-load and full-load voltages taken as a per cent of the full load voltage. Expressed as a formula, this is

$$\text{Regulation} = \frac{\text{No-load voltage} - \text{full-load voltage}}{\text{Full-load voltage}} \times 100.$$

equation (23)

The lower the percentage voltage regulation of a generator, the more nearly constant is its terminal voltage. Of course, this refers to changes in voltage corresponding to gradual changes in load, and does not refer to large momentary fluctuations in voltage accompanying rapid load changes.

12. Losses in Generator

(a) *Stray Power Losses:*

(1) *Iron or Core loss.* The losses of energy occurring in the iron are of two classes and are due to Eddy Currents and Hysteresis.

Eddy-current losses are due to the eddy currents, sometimes called Foucault currents, which circulate in the armature core. These serve no useful purpose and finally the electrical energy present is converted into heat. The iron armature core is a conductor of electricity and it cuts a magnetic field, just as the copper conductors cut the field. In so doing, e.m.f.'s are induced, which cause the eddy currents to circulate through the core. By laminat-

ing the armature core parallel to the direction of rotation (that is, perpendicular to the axis of rotation), the eddy currents are subdivided into a number of very small currents circulating in each thin disk. Assuming that the resistance to the eddy-current flow is approximately the same with an increased number of laminations, then the *loss* will be greatly reduced by subdividing the current, since loss in watts equals current squared times resistance. A numerical example will make this clearer. With a resistance of one ohm and a current of ten amperes, the energy loss is 10 times 10 times 1 = 100 watts; if the ten amperes is subdivided into two currents of 5 amperes each, flowing through resistances of one ohm each, then the loss will be 5 times 5 times 1 = 25 watts in each circuit or a total of 50 watts. This illustrates how laminations will cut down the energy loss even if the sum of the small eddy currents adds up to the same total amperage as before laminating.

Hysteresis. Hysteresis loss occurs mainly in the armature core and is caused by the resistance offered by the iron to changes of polarity. After the magnetizing force has disappeared, iron still retains some of its magnetism and moreover it also resists a change. Hysteresis is analogous to mechanical inertia. It acts like friction to prevent a change. The armature core is subjected to ever-changing magnetization, as it passes under first a north and then a south pole. The resultant loss of energy due to hysteresis will show itself as heat and there will also be an increased drag on the armature which will have to be overcome by the prime mover. The heating due to Eddy Current Loss and Hysteresis usually mani-

fects itself in the armature teeth where the flux density is high. Hysteresis loss can be reduced by using electrical steel having low retentivity and it can also be lowered by annealing. It has been found that the hysteresis loss in the iron is increased after the laminations are punched and hence it is very necessary to anneal the laminations.

(2) *Friction or Mechanical Losses.* These may be subdivided into three groups:

Bearing friction. This varies directly with the speed of the armature, but at constant speed there is very little variation of friction with load, so it may be taken as a constant value.

Brush friction. Wherever a stationary part touches a moving part, as in the case of the brushes resting on the commutator, friction will result. Brush friction follows the same laws as bearing friction.

Windage. The air offers a frictional resistance to the rotation of the armature and this is called "windage." This is independent of load conditions, but varies approximately as the square of the speed.

All frictional losses retard the rotation of the armature, thus requiring increased power from the prime mover and moreover the frictional losses are converted to heat.

(b) *Copper Losses.* Whenever current flows through any conductor, there will be a loss which will vary directly with the resistance of the conductor and also directly with the square of the current. The energy thus lost is converted into heat energy. The copper losses in the generator are subdivided as follows:

(1) *Loss in armature winding.* This loss increases as the square of the load.

(2) *Loss in field windings.* This loss is practically independent of the load in the shunt winding. In the series winding it increases as the square of the load.

(3) *Losses in other windings.* Any other windings, such as interpole windings, compensating coils, etc., will have a copper loss and since these windings are in series with the load, the loss will increase with the square of the load current.

13. Efficiency of Generator

(a) *Definition.* The efficiency of a generator is the ratio of its useful output to its total input. It is usually expressed in per cent. No machine can ever give out more energy than, or even as much as, is put into it. Hence it is impossible for a generator to have an efficiency of 100 per cent. No matter how small the losses are, they can never be entirely eliminated. The "commercial efficiency" is considered as the product of the electrical efficiency of the generator and the mechanical efficiency of the engine generator set. Commercial efficiencies vary from 70 per cent in very small generators to 90 per cent in large ones. Low efficiency will always be accompanied by high heating since the large losses are converted to heat.

(b) *How determined:*

(1) *Directly.* The efficiency may be determined directly by measuring the power expended by the prime mover and measuring the output of the generator. If both are expressed in the same units, the latter divided by the former will give the commercial efficiency. The engine output may be determined from indicator cards,

while the generator output may be found by connecting an ammeter in series with the load and a voltmeter across the terminals of the load and multiplying volts times amperes.

(2) *Indirectly.* The efficiency may be determined indirectly by measuring the losses and calculating it from the formula:

$$\text{Efficiency} = \frac{\text{Output}}{\text{Output plus Losses}}.$$

Equation (24)

In this method, it is necessary to determine only total friction losses and iron losses by test since other losses and also output can be calculated. The copper losses are calculated in the following way: The square of the armature current times the armature resistance will give the loss, in watts, in this winding. In like manner, the current through the series field squared, times the resistance of this winding will give its copper loss in watts. The loss in the shunt field may be calculated in the same manner or it may be obtained by multiplying the voltage across the shunt winding by the amperage in this winding.

The various Stray Power Losses may be determined together by running the generator as a motor, unloaded, separately exciting the field at its normal value so that the motor will run at the same speed as it did as a generator. In this case the input, as obtained by an ammeter in the armature circuit and a voltmeter across the terminals, is equal to the stray power losses. This is true since the copper loss in the armature is negligible at no load, and hence all the power input is consumed in overcoming friction, eddy current and hysteresis losses.

The full load output may be calculated by referring to the name plate, which gives the full load current and the terminal voltage. (Usually output in kw. or hp. also.) Output at any other load may be calculated, knowing these values.

Having obtained the output and added up the total losses, the efficiency may be calculated from the formula given above. There are various other indirect methods of obtaining the efficiency of a generator. Where two generators of about the same size are available, "pumping back" or "opposition" methods are often most suitable. In these tests the two generators are connected both electrically and mechanically and are so driven that one acts as a generator and the other one as a motor. Since the motor drives the generator and the generator gives out current to run the motor, the small amount of power which is supplied from an external source is a measure of the losses. In the "Blondel" method the electrical losses are supplied electrically and the mechanical losses are supplied mechanically and hence this seems to be the most rational of these opposition tests. In the "Hutchinson" test all losses are supplied electrically, the copper losses being supplied by means of a booster and the iron and friction losses from the line. This method is theoretically correct but is rather complicated. More complete descriptions of these tests can be obtained from the various electrical handbooks.

14. Armature Reaction

(a) *Definition.* Armature reaction is the effect of armature flux upon field flux. To illustrate this definition consider a

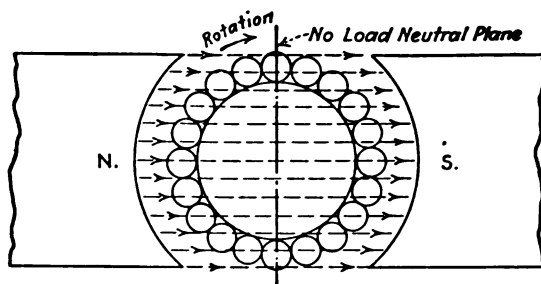


FIG. 49. — Illustration of armature reaction. Generator shown rotating at no load.

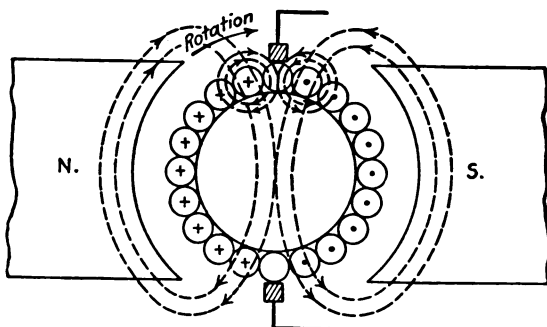


FIG. 50. — Illustration of armature reaction. Current is being drawn from the generator.

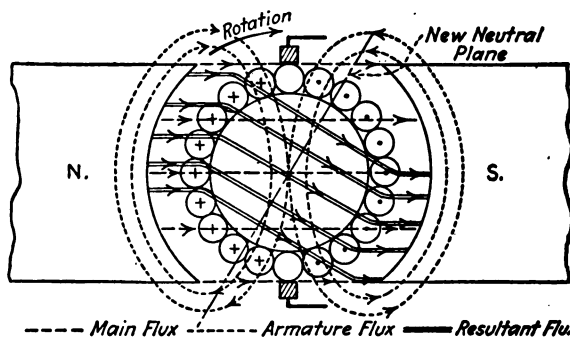


FIG. 51. — Illustration showing the effect of armature reaction.

two-pole generator as shown in Figs. 49, 50, and 51. When this generator is rotating at no load the field is as shown in Fig. 49. As soon as the external circuit is closed and current flows in the armature windings, the conductors under the north pole will have current flowing in one direction, while those under the south pole will have current flowing in the reverse direction. The current direction may be determined by the right-hand rule. Current flowing "in" is represented in the figure by a cross to show the end of the arrow while current flowing "out" towards the observer is represented by a dot to show the point of the arrow. Figure 50 shows the magnetic field due to the armature current. The main field magnetism is not shown in this figure. If the armature core is considered as a large electromagnet with current flowing out of the conductors on the right-hand side and into those on the left-hand side (in other words, if it is considered as a solenoid having a belt of current flowing around it from right to left) it will then be clear, from the corkscrew rule, that the top will be a south pole and the bottom a north pole. The direction of the total armature flux can also be determined by examining the flux around each separate conductor. To avoid confusion in the figure, these separate fluxes are only shown around a few conductors near the top. In Fig. 51 the field flux and the armature flux are shown and also the resultant flux. From this figure, the effects of armature reaction may be observed. The field (resultant) has been shifted forward in the direction of rotation, and moreover it has been distorted. *Distortion* of the field may be defined as a strengthening of the magnetism in some places and a weakening in others. It can readily be seen that a uniform field is more

desirable than a distorted one. By examining the direction of the field flux and the armature flux (see arrows) it is seen that where the arrows are in the same direction, the field is strengthened, while where they oppose each other, the field is weakened. The strengthening occurs at the leading pole tips and causes the shifting of the field.

(b) *Neutral plane.* The neutral plane exists where the armature coil is moving parallel to the lines of force. At that place, the coil cuts no lines of force. At *no load*, the neutral plane is located halfway between the north and

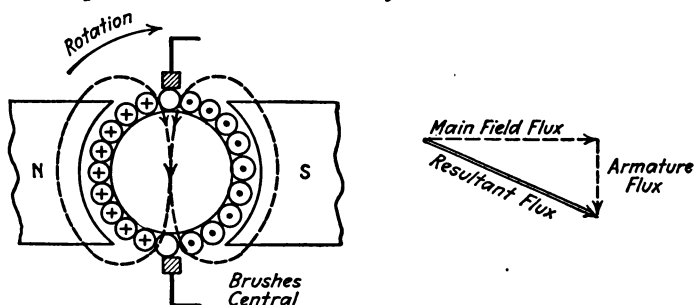


FIG. 52. — Armature reaction illustrated by means of vectors. Brushes shown at the central position.

south poles. As current is drawn, armature reaction shifts the neutral plane forward.

(c) *Illustration of action by use of Vectors.* — Effects of Brush Shifting: A vector is a line here used to represent a magnetic field (usually used to represent forces). The direction of the vector represents the direction of the field and its length represents the relative strength of the field. The action of armature flux upon field flux (armature reaction) may be shown in a clear manner by the use of vectors. Vectors will also show how shifting the brushes will affect the strength of the resultant flux. In Fig. 52, with the

brushes at the central position, the armature flux acts at right angles to the main field flux, the result being shown by a shifting of the field, due to the cross-magnetizing

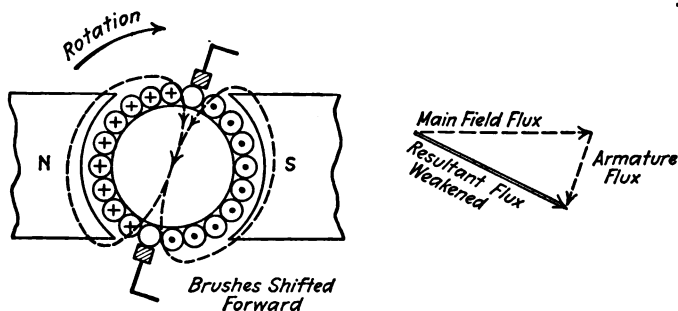


FIG. 53. — Brushes shifted forward in the direction of rotation. Vector diagram shows how resultant flux is weakened.

action. Figure 53 shows the effect of shifting the brushes forward. In this case the armature flux may be resolved into two components. The one part exerts a cross-mag-

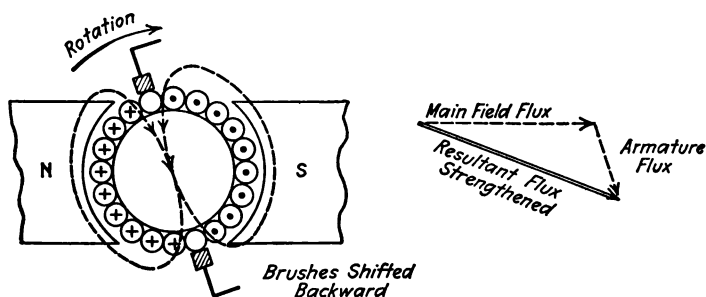


FIG. 54. — Brushes shifted backward against the direction of rotation. Vector diagram shows way in which resultant flux is strengthened.

netizing effect while the other exerts a demagnetizing effect. As a result, the field is not only shifted, but also is weakened. This is indicated by the shorter resultant flux line. The result of shifting brushes backwards is shown in Fig. 54.

In this case a part of the armature flux aids the main flux and hence the resultant field is strengthened. From the above discussion it can be seen that no matter how the brushes are shifted, the resultant flux is shifted forward in the direction of rotation.

(d) *Effect of Armature Reaction shown by Flux Diagram.* The north and south poles of the assumed generator can be represented as laid out in a plane (see Fig. 55) and the strength

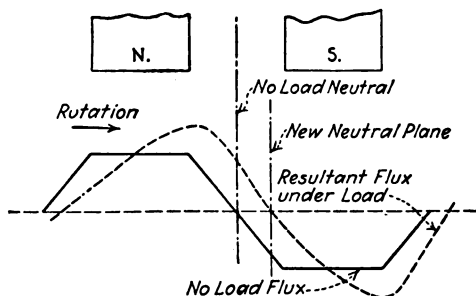


FIG. 55.— Flux distribution diagram showing how resultant flux is distorted and shifted forward under load.

of the magnetic field at any point may be represented by the distance of the lines from the horizontal dotted line. North polarity magnetism is represented as being above the dotted line, while south polarity is shown

below this line. The no-load neutral plane is shown half-way between the poles. The full line shows the flux distribution at no load, while the dotted line shows the effect of the armature reaction. It represents the resultant flux, shifted forward, distorted, weakened under the lagging pole tip, and strengthened under the leading pole tip. The point of zero flux is called the "new neutral plane."

(e) *Methods of Reducing Armature Reaction.* The best method of neutralizing the effects of armature reaction is by the use of Compensating coils.

(1) *Compensating coils.* These coils are laid in slots in the faces of the main poles. They are so wound that the

direction of current in them will be opposite to the direction of the current in the armature windings passing under them. They are connected in series with the armature coils and the load, in order that they may give a flux equal and opposite to the armature flux at all loads. They thus neutralize armature reaction and prevent distortion of the field. They are usually used in connection with interpoles and are especially adapted for rapidly fluctuating loads.

(2) *Methods which reduce the armature flux by introducing reluctance in its path.* Among these methods may be classed:

Slotted pole shoes and slotted pole cores. The slots lie parallel to the axis of rotation and hence do not materially interfere with the main flux but do offer considerable resistance to the passage of the armature flux.

(3) *Use of saturated pole tips.* By constructing the pole shoe so that the forward pole tip is saturated, it is possible to reduce distortion to a considerable extent. It has already been noted, that considerable effort is necessary to weaken or strengthen a saturated field. Hence the armature flux is less able to produce distortion. One method of construction to obtain saturated pole tips is to punch the laminations with tips on one side only and then assemble them, alternating the tips on either side. In this way there is only one-half as much material in the tips as in the rest of the pole and consequently the flux will be more crowded in them and they will be saturated.

(4) *Eccentric pole shoes.* These are made eccentric with the armature, so that the pole centre will be closer to

the armature than the tips, and hence there will be a relatively strong field at this point.

15. Commutation

(a) *Conditions for Sparkless Commutation.* A complete reversal of current in the coil or coils undergoing commutation, is necessary in order to get “black” or “sparkless” commutation. The coil undergoing commutation is called the “short-circuited” coil, since the brush, in touching two

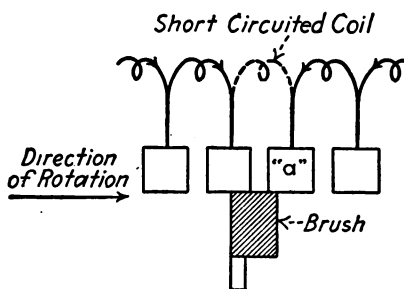


FIG. 56.—Coil undergoing commutation.

commutator segments, acts as a dead short-circuit. Hence this coil is useless for purposes of inducing a useful e.m.f. Moreover, the more current flowing in the short-circuited coil, the greater will be the sparking. Assume that the commutator is moving in the

direction shown by the arrow, and that current is flowing towards the brush as shown in Fig. 56. If complete reversal has not taken place before the brush leaves segment *a*, or if current still circulates in the short-circuited coil, for any reason, this current will be obliged to jump from segment *a* to the brush when that segment leaves the brush. It is obvious that this small current in the short-circuited coil would not be able to buck the rush of current in the coils to the left and hence a spark from segment to brush is the only possibility.

(b) *Electrical Causes of Sparking:*

(1) *Armature Reaction.* Armature reaction causes sparking by causing an e.m.f. to be induced in the short-cir-

cuted coil. Although the e.m.f. induced may be small still a relatively large current may flow in the coil, since the short-circuited path has low resistance. Sparking then follows as explained above. The way in which armature reaction acts to cause this induced e.m.f. in the short-circuited coil

is as follows: At no load the coils moving through the no-load neutral plane (halfway between the north and south poles) cut no flux. When current is drawn from the generator, armature reaction shifts the flux forward in the direction of rotation, and the coil in the central position (short-circuited coil) now cuts flux. The e.m.f. induced causes current to flow in the short-circuited coil, and moreover the direction of this current is op-

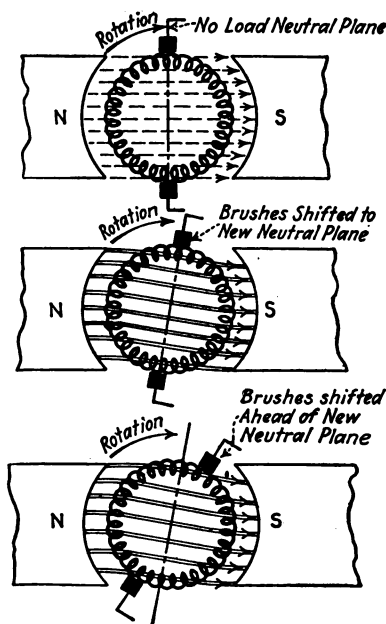


FIG. 57. — Method of shifting brushes in order to get sparkless commutation shown in three steps.

posite to that desired. It should be noted in Fig. 57 that the brushes are represented as resting on the coils instead of on commutator segments. This is so drawn, in order to make the sketch clearer. By shifting the brushes to the "new neutral plane," the short-circuited coil no longer cuts flux and hence the effects of armature reaction are overcome.

(2) *Self-induction.* As a coil undergoes commutation, the current in it changes direction. Before the commutator segment connected to it passes under the brush, the current is in one direction and afterwards the current is in the reverse direction. Changes in current are always accompanied by self-induction. When the current is decreasing, the e.m.f. of self-induction is in the same direction, thus tending to prevent the decrease. When the current is increasing in the reverse direction, the e.m.f. is in the opposite direction, thus tending to prevent the increase. In each case, the e.m.f. of self-induction acts in such a direction as to oppose the desired commutation. As a result, the change of current direction does not take place during the time that the commutator segment passes the brush. Hence there is an excess of current in the wrong direction in the short-circuited coil and sparking follows.

(c) *Sparkless Commutation by Shifting Brushes.* As explained above, the effects of armature reaction may be overcome by shifting the brushes forward in the direction of rotation until the short-circuited coils lie in the new neutral plane. This will not prevent sparking, however, for the effects of self-induction will still be present. In order to overcome the effects of self-induction also and obtain sparkless commutation, the brushes must be shifted forward even further, so that the short-circuited coil will lie a little bit in advance of the new neutral plane. The short-circuited coil now cuts flux in the reverse direction and by experiment it is possible to find the place where an e.m.f. will be induced in the short-circuited coil just equal and opposite to the e.m.f. of self-induction. The result is "sparkless com-

mutation." The method and effect of brush shifting can be readily seen by reference to the flux distribution diagram, shown in Fig. 58.

(d) *Sparkless Commutation by Use of Interpoles:*

(1) *Definition of Interpole.* Interpoles are small magnetic poles placed between the main field poles for the purpose of obtaining better commutation.

(2) *How connected.* Interpole windings are connected in series with the armature winding and the load. Hence, an increase in load, which is accompanied by an increase

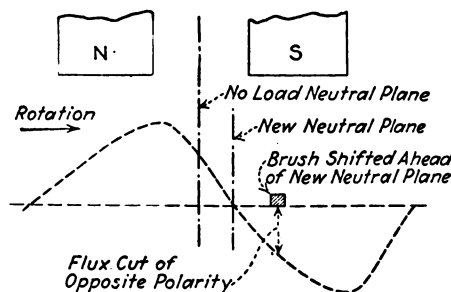


FIG. 58.—Flux distribution diagram illustrating method and effect of shifting brushes in order to get sparkless commutation.

in armature reaction, will also be accompanied by increased interpole strength. A variable resistance is usually shunted around the interpole winding for the purpose of obtaining the correct amount of compensation.

(3) *Action of Interpole.* The action of the interpole is exactly analogous to the shifting of the brushes but when interpoles are used brush shifting is dispensed with and the flux is shifted instead. Thus it has been shown that armature reaction shifts the flux ahead in the direction of rotation. As a result, with no interpoles, the short-

circuited coil cuts flux if it is not advanced by shifting the brushes. By introducing an interpole at the no-load neutral plane, it is possible to always prevent the short-circuited coil from cutting flux or if so desired, it is possible to have it cut flux in the reverse direction to overcome the effects of self-induction also. Interpoles do not prevent distortion of the field due to armature reaction, but they do prevent distortion locally, at the points of commutation. It can be seen, from the flux distribution diagram, Fig. 59, that the polarity of the interpole in a

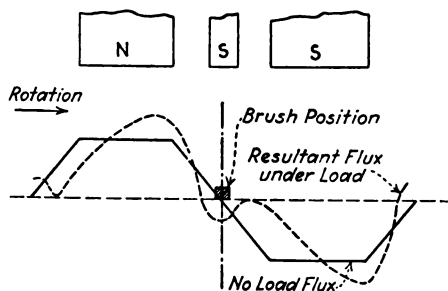


FIG. 59. — Flux distribution diagram with interpoles showing how interpole shifts the flux back.

generator must be the same as that of the pole being approached. Thus, if the rotation is from a north to a south pole, the interpole must be a south pole. This serves to shift the flux back, in place of shifting the brush ahead. The strength of the interpole must be such as to prevent armature reaction from shifting the flux forward in the commutating plane and also must be such as to provide sufficient flux in the reverse direction to supply an e.m.f. equal and opposite to the e.m.f. of self-induction. Sparkless commutation can then be obtained.

(e) *Resistance Commutation.* The methods described above

for obtaining sparkless commutation could be classed under the head of e.m.f. commutation, since they depend upon the inducing of an e.m.f. in the short-circuited coil. The use of carbon brushes is an auxiliary means of reducing sparking and is classed as "*resistance commutation*." The higher the resistance of the short-circuited coil and of the brush and brush contact, the more rapid will be the commutation. In other words, the resistance of this local circuit will have just the opposite effect of the inductance. However, the brush forms a part of the main or load circuit, and too great a resistance will result in a voltage drop and also increased large heat loss. Hence a compromise is necessary. The carbon brush aids in the reversal of current in the short-circuited coil, but cannot accomplish this reversal alone and must be accompanied by some form of e.m.f. commutation.

16. Capacity of Generators

(a) *Size of armature windings.* Overheating will result if current is drawn from the generator, of greater value than the safe carrying capacity of the armature windings. The insulation will char at about 178 deg. F. so current should never be drawn from a generator which will raise its temperature to this value.

(b) *Commutation.* The output of a generator is limited by excessive sparking which will occur (in machines without interpoles) at heavy loads, due to armature reaction.

(c) *Ventilation.* Proper ventilation will increase the capacity of a generator by radiating the heat away from it, thus keeping the temperature at a safe value. If the machine is poorly ventilated, this in itself may put a limit to the output of the generator.

(d) *Excessive voltage drop.* In some generators, increased current output will be accompanied by excessive drop in terminal voltage. This will automatically prevent further increase in current.

17. Three-wire Generator

(a) *Principle of operation.* The three-wire generator has a closed-circuit armature winding and commutator and brushes like other direct-current generators. It differs from them, in that taps are led out from symmetrical points in the

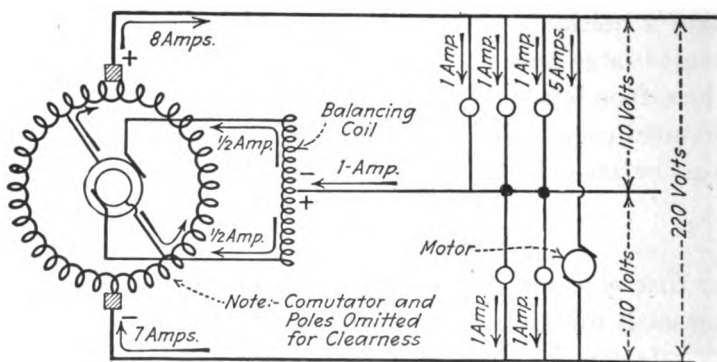


FIG. 60. — Elementary diagram of a three-wire generator.

armature winding to slip rings. From the brushes on the slip rings, connections are made to a reactance coil (or coils) and the neutral wire is connected to the central point of the reactance coil. By this method of construction, the voltage between either outside wire and the neutral will be kept at one-half the voltage between the two outside wires. An elementary diagram is shown in Fig. 60 of a three-wire generator having two taps to the armature winding. The generator may be constructed with three or even four taps and with two reactance coils instead of one, but the prin-

ciple of operation is the same in all cases. The current in the armature winding reverses its direction each time the coils pass through a field of different polarity (as explained above). Hence an alternating current flows into the reactance coil. This coil has a laminated iron core and although it has low resistance, it has high reactance (i.e. its high coefficient of self-induction acts to prevent the flow of alternating current). Hence the alternating current which does flow in the reactance coil is of small value and in reality is a magnetizing current. If the generator has equal loading between the positive wire and the neutral and between the negative wire and the neutral, no current will flow in the neutral wire. If the positive side carries the heavier load, current will flow back to the generator through the neutral wire. The current in the neutral wire will be equal in amount to the difference between the current in the positive wire and that in the negative wire. Since the neutral wire is connected to the center of the reactance coil, the current will divide equally at this coil and then will flow through the slip rings, one-half to one side of the armature windings and one-half to the other. From there, the current will flow back to the positive brush. If the connection of the neutral wire to the reactance coil were broken, with the heavier load on the positive side, the excess current would have to flow through the higher resistance on the negative side, and hence there would be higher voltage between the neutral wire and the negative than between neutral and positive. The reactance coil automatically maintains the same voltage between neutral and either outside wire and hence it is sometimes called a "balancing coil." In the case of heavier load on the positive side, the flow of current

through the balance coil subdivides as explained above and thence flows through the armature winding in such a direction as to increase the voltage between neutral and positive to the correct amount at all positions of rotation. When the heavier load is on the negative side, the action is the same, except that the current now flows out from the neutral wire and then its direction is such as automatically to prevent voltage drop on the negative side.

(b) *Advantage of three-wire system over two-wire system:*

(1) *Saving in copper.* With the same voltage drop and with the neutral wire of the same size as the two outside wires, there will be a saving of 25 per cent by weight, of copper in the use of a three-wire system as compared to a two-wire system. Hence a three-wire system is more economical for transmitting direct-current electrical energy for a distance than is a two-wire system.

(2) *Two voltages available.* Since motors are, in general, more efficient when operated at 220 volts and lights last longer on 110 volts, the use of a three-wire system makes both these voltages available. Moreover, in shops, where variable-speed motors are used, the two voltages will give greater flexibility of operation.

(c) *Allowable unbalancing.* The unbalancing on either the positive or the negative side should never exceed 15 per cent of the total load. Three-wire generators are built with compound windings and with interpoles and they may be operated in parallel.

18. Generator Operation

(a) *Measuring instruments necessary.* In the operation of a generator, it is necessary to know the terminal voltage and the current being drawn from the machine. Hence all

generators are usually fitted with a voltmeter, connected across the terminals, and an ammeter in series with one of the brushes and the load. These instruments are located on a switchboard, which is usually in the immediate vicinity of the generator. A wattmeter or watt-hour meter may also be provided for measuring power output.

(b) *Protective devices.* An overload circuit-breaker is usually located in series with one of the brushes and the load. In some cases the circuit-breaker is located on both the positive and the negative sides, but this is not absolutely necessary. The circuit-breaker is located on the switchboard, usually at the top. Fuses may also be provided. The various switches for opening the circuit are located on the front of the board and also the handle for regulating the shunt field resistance. The resistance itself is on the back of the board. The heavy copper bus bars are on the back of the switchboard also.

(c) *Shunt Generator Operation:*

(1) *Starting.* In starting up a shunt generator, it is necessary to bring it up to rated speed first, load switch being left open. It is better to start with all the resistance "in," in the shunt field rheostat. By gradually cutting out this resistance the generator will build up to rated voltage. The circuit-breakers should be closed next and finally the load switch. It is good practice to have the voltage of the generator slightly higher than rated voltage before closing the load switch, in order to allow for the increased voltage drop when the load is thrown on the machine. However, the voltage may be regulated to the desired value by the shunt field rheostat, after the switch has been closed.

(2) *Stopping.* It is advisable to reduce the load as much as possible before stopping. The shunt field resistance should be thrown all "in," in order to weaken the field as much as possible. The circuit-breakers should next be tripped by hand, and the load switch opened. The generator prime mover can then be shut down. If there is a switch located in the shunt field circuit, this should not be opened until all the resistance is "in," since otherwise the high inductance of the shunt winding may cause a momentary high e.m.f. of self-induction which might injure the winding. By tripping the circuit-breaker before the load switch, the arc takes place between carbon contact pieces instead of between the switch blades and clips. This protects them from pitting or fusing.

(3) *Shunt Generators in Parallel.* Shunt generators can be operated in parallel, but for best results the two machines should have similar characteristics. Care should be taken that the positive terminal of one machine connects with the positive terminal of the other. In throwing a shunt generator in parallel with another one, its voltage should be adjusted so that it will be slightly higher than the one carrying the load. When the load switch is thrown the voltage of the two machines will be the same, but if one machine has more excitation than the other, it will carry more than its share of the load. The load can be equally divided between the two machines by adjusting the shunt field rheostats. It is essential that both machines have the same speed, before an attempt is made to run them in parallel. Since the voltage of a shunt generator falls with increased load, this characteristic serves to make the operation of shunt

generators in parallel a stable one. For if one machine starts to carry more than its share of the load, its voltage tends to drop and the load is then automatically shifted to the other machine.

(d) *Compound Generators:*

(1) *Starting and stopping.* In starting and stopping compound generators, the same procedure should be followed as outlined above for shunt generators.

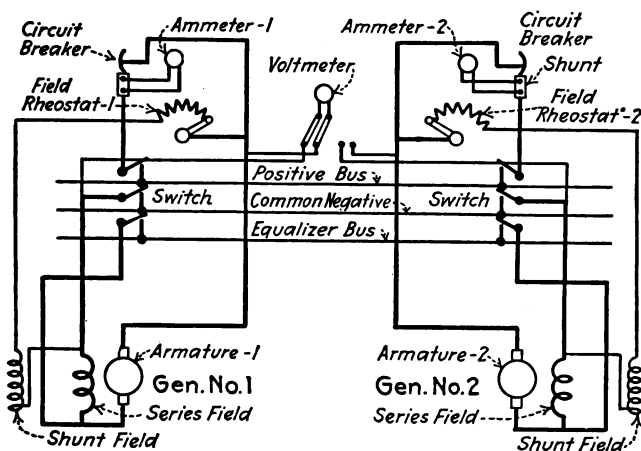


FIG. 61. — Switchboard wiring diagram for operating compound generators in parallel.

(2) *Requirements for parallel operation.* The same requirements are necessary in operating compound generators in parallel as for shunt generators but in addition the series windings must be interconnected as shown in Fig. 61 by a conductor of very low resistance. This conductor is called an "equalizer."

(3) *Action of equalizer.* The presence of the series field necessitates the use of the equalizer and this simply

amounts to the connecting together of the brushes of like polarity on each machine. If one generator starts to carry more than its share of the load, its series winding will obtain greater excitation and the tendency would then be for it to take more and more of the load until it drives the other generator as a motor or until the circuit-breakers trip. The equalizer will prevent this, for as soon as the series field of one machine carries more current than the other, an equalizing current will flow to the other machine. This current will always flow when the terminal of one machine is at a lower potential than the terminal of the other. The equalizing current will flow through the series winding of the second machine, thus raising its voltage until it carries its share of the load. The speed of compound generators operating in parallel should be fairly constant and their characteristics should be the same. An over-compounded generator will not operate satisfactorily in parallel with a flat-compounded one. In general, flat-compounded generators will operate in parallel better than will over-compounded machines.

(4) *Throwing compound generator in parallel with another.* To perform this operation, first see that all switches connecting one generator with another are open. Next throw all the resistance "in," in the shunt field rheostat. Then bring the generator up to speed. The rheostat should then be adjusted until the voltage of the generator builds up to a slightly higher value than the machine in operation. The circuit breaker should be closed next and then the equalizer switches of both machines. The voltages of the two machines should again be checked and then the bus-bar switch can be closed. If the negative side and

the positive side have separate switches, the negative switch should be thrown first. When the two machines are connected in parallel, the load should be adjusted equally between them by means of the field rheostats. (5) *Cutting out compound generator which is in parallel with another.* Adjust the rheostat of the machine to be cut out, until the ammeter on the other machine shows it to be carrying the entire load. Then trip the circuit breaker and open the bus switches and finally the equalizer switch. The prime mover may then be stopped.

19. Generator Troubles

(a) *Failure to build up:*

(1) *Loss of residual magnetism.* This may have occurred on account of a jar or through a momentary reversal of current. The generator should be stopped and the pole can then be tested by seeing whether it will attract a nail or other piece of soft iron. This trouble can be remedied by exciting the field from an outside source for a short while.

(2) *Reversed field.* The entire field may be reversed or one or more poles may have their connections reversed. The poles should be tested with a small compass and should show alternate north and south polarity. If this is not the cause of the trouble, the entire field connection should be reversed.

(3) *Ground in field winding.* In this case the poles will show only weak magnetism and a test for a ground will reveal the trouble. The same applies to a short-circuit also.

(4) *Open circuit in field or armature.* Sometimes this is

merely due to poor brush contact or loose connections. If this is not the trouble the windings can be tested for open circuit with a magneto.

(5) *Brushes not correctly located.* Sometimes the generator fails to build up due to incorrect brush location. Proper position may be determined by experiment, shifting the brushes until machine commences to build up.

(b) *Failure to carry load:*

(1) *Series field reversed.* In a compound generator, if the machine refuses to carry increased load, it is probable that the series field is bucking the shunt field. In this case, its connection should be reversed.

(2) *Broken connection.* The vibration of the machine may open a connection to the shunt field or a terminal connection. In this case, the machine will suddenly lose the load. The usual tests for open circuits will reveal the trouble.

(c) *Excessive sparking:*

(1) *Electrical causes.* Armature reaction and self-induction may cause excessive sparking as the current is increased. Brush shifting may remedy this to a certain extent. However, if too much current is being drawn, either on account of overload or a short-circuit or ground in the armature winding, the machine must be stopped and the fault located. A short-circuited armature coil will show local heating or it may be burnt out and will then have to be renewed. If the sparking is due to an overload on the external circuit, the entire armature will be hot. Open circuits, either in the armature winding or the field, will also cause sparking. If the open is in the armature, the commutator will be burnt near the

break. The method of locating the exact open-circuited coil will be explained under "tests." If the open circuit is in the field the trouble will also be indicated as explained under (a) (4).

(2) *Mechanical causes.* Sparking may be due to dirty commutator, brushes too hard or too soft, loose brush holders, rough or uneven commutator, or improperly fitted brushes. These troubles are usually self-evident, as is their remedy.

(d) *Excessive heating:*

(1) *Commutator and brushes.* If unaccompanied by sparking, this may be caused by too great a brush pressure or by conduction from other parts. If accompanied by sparking, trouble should be looked for, as indicated above. A short-circuit between commutator segments or too small a brush pressure may also cause local heating, unaccompanied by sparking.

(2) *Armature.* If the armature becomes heated, due to conduction from the bearings or commutator, these parts will be hotter than the armature itself. If the core is hotter than the windings, after a short run, the heating may be due to eddy currents and hysteresis. In this case, the design of the machine is poor, and there is no means of remedying the fault. Short-circuits or grounds, either in the external circuit or in the armature winding will cause heating due to the extremely heavy current drawn. Continuous overload will also cause the armature to heat up.

(3) *Field windings.* If the heating is due to conduction, the trouble may be located as indicated above. If due to eddy currents in the pole face, the magnet core will be

hotter than the winding and the machine is defective. If due to short-circuits or grounds, the heavy field current will cause the coils to become exceedingly hot. The insulation may become charred and burned. Methods of locating the faulty coil will be given under "tests." Moisture in the field windings will sometimes cause them to overheat.

(4) *Bearings.* Bearings may heat up due to want of lubrication or on account of oil rings sticking. They should be inspected regularly, and if the ring is not rotating it can be started again by pushing it with a small stick. The bearings should be felt at frequent and regular intervals in order to locate any trouble at the start. Dirty or gritty bearings will also cause heating as will poor bearing alignment or improper clearance between shaft and bearing. Other causes of hot bearings are rough shaft, rubbing of shoulder against bearing, or bent shaft.

20. Generator Tests

(a) *Short-circuit:*

(1) *Armature winding.* If a coil is short-circuited it will usually first manifest itself by the smell of burning insulation. The short-circuited coil itself will be found to be very much hotter than the other coils. If a number of coils are short-circuited, it will be necessary to use a bar-to-bar method in order to exactly locate the trouble.

Bar-to-bar test. The armature should be removed and put into a holder, as shown in Fig. 62, so that it will be free to turn. Contact can be made with the commutator at two opposite points, by means of pieces of thin brass fastened to the holder. (An old soap box will often serve

the purpose of supporting the armature.) A low-voltage direct current should then be sent into the armature. The leads from a milli-voltmeter should be fitted with sharp points, in order to get good contact with the commutator, and as the armature is slowly turned, a test should be made with the milli-voltmeter from bar to bar entirely around the commutator. If the armature coils are in good condition, there will be the same voltage drop

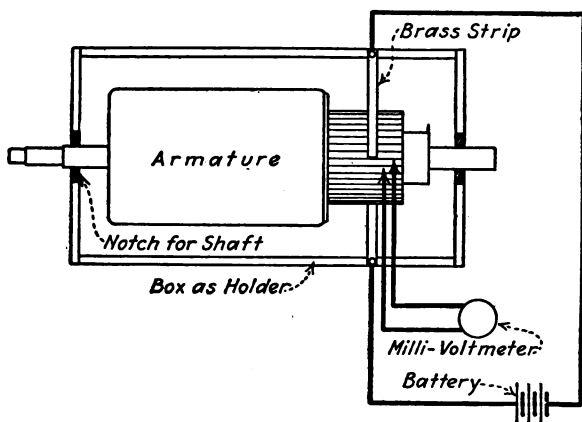


FIG. 62. — Connections for making a bar-to-bar test.

between every two adjacent bars on the commutator. However, if there is a short-circuited coil, the voltmeter will show no deflection, or else a much smaller deflection. If there were an open-circuited coil the milli-voltmeter would be burned out, so it is necessary to first test for open-circuit by using a voltmeter of the proper range. The bar-to-bar test is performed as above, but, in this case, there is no deflection unless there happens to be an open-circuit, in which case the voltmeter will show a

deflection equal to the amount of the voltage being applied.

(2) *Field winding.* It may be possible to locate the short-circuited winding by testing the magnetism with a piece of iron. The faulty coil will not attract the iron as strongly as the good coils. A surer test is to send current through the field winding and then test each coil separately with a voltmeter. By holding the voltmeter leads at the terminals of each spool, the voltage drop across each separate winding can be obtained. If one of the coils is short-circuited, the voltage drop across it will be greatly lessened.

(b) *Ground:*

(1) *Armature winding.* While a single ground will not cause immediate trouble, it is better to locate it, since two grounds will be the same as a short-circuit. This is especially the case where both grounds are in the same coil. The ground can be located by winding a bare wire around the commutator and sending a current through it, connecting the return lead to the armature core. The grounded coil will show magnetism which can readily be detected with a small compass.

(2) *Field winding.* In order to locate a ground in the field windings, each coil must be tested separately, by connecting one terminal of a magneto to the coil, and the other terminal to the iron magnet core. If the magneto "rings through," there is a ground in that coil.

(c) *Open circuit:*

(1) *Armature winding.* In the case of an open circuit in an armature coil, the commutator bars nearest the broken coil will flash violently when the armature is

turned over slowly. To exactly locate the faulty coil or coils, the bar-to-bar test should be performed, as explained under "short-circuits."

(2) *Field winding*. If there is an open circuit in the field winding, the generator will not become excited. If voltage is applied at the field terminals, the break can easily be located with a voltmeter. The open-circuit can be found by connecting one voltmeter terminal to

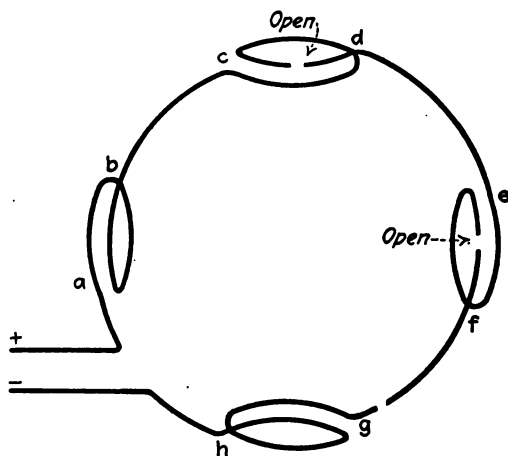


FIG. 63.—Diagram to illustrate method of locating open circuits in field windings of generators.

one field terminal, then touching the various field coil terminals one after another, with the other voltmeter lead. After the break is passed, the voltmeter will deflect. If there are two breaks, they can be located in a similar manner. Thus, as an example, suppose there are four field coils, *a-b*, *c-d*, *e-f*, and *g-h*. (Fig. 63.) Assume that there are open circuits between *c* and *d*, and also between *e* and *f* and that an e.m.f. is impressed upon

the circuit at the terminals marked plus and minus. If one of the voltmeter leads is connected to the plus terminal and the other one is touched to *b* there will be no deflection. When the voltmeter lead is touched to *d*, there is no deflection either, on account of the second break between *e* and *f*. When touched to *f*, however, the voltmeter will show a large deflection. This proves that the remainder of the circuit from *f* to the negative terminal is O.K. The voltmeter lead is now connected to *f*, and the other lead is then taken from the positive terminal and touched to *b*. Since it still deflects, the fault cannot lie between *a* and *b*. It is next touched to *d* and there is then no deflection. This shows that the open circuit is between *c* and *f*. Since there will be no deflection if the other lead is moved from *f* to *e*, this conclusively locates the open circuits as being between *c* and *d* and *e* and *f*.

Outline of Lesson 8 — DIRECT-CURRENT MOTOR

- 1. DEFINITION OF A MOTOR.**
- 2. FUNDAMENTAL PRINCIPLE OF MOTOR — MAXWELL'S LAW OF MOTOR ACTION:**
 - (a) Motor action is Magnetic action.
 - (b) Generator as Motor.
 - (c) Generator Action in Motor.
- 3. ESSENTIALS OF ALL DIRECT-CURRENT MOTORS.**
- 4. CONSTRUCTION OF MOTOR.**
- 5. ACTION OF COMMUTATOR.**
- 6. USE OF MULTI-COILS.**
- 7. FACTORS DETERMINING AMOUNT OF MAGNETIC FORCE EXERTED:**
 - (a) Armature Current.
 - (b) Field Strength.
 - (c) Length of Conductor.
- 8. MOTOR TORQUE:**
 - (a) Definition.
 - (b) Unit of measurement.
 - (c) Torque determined by Counter-torque.
 - (d) Torque independent of Speed.
 - (e) Torque and Power.
 - (f) Torque expressed as an equation.
 - (g) Numerical example.
- 9. FACTORS DETERMINING MOTOR SPEED:**
 - (a) For constant speed, torque must balance counter-torque.
 - (b) Torque developed by means of armature current.
 - (c) Armature current limited by counter e.m.f.
 - (d) Counter e.m.f. limited by speed.
 - (e) What determines speed finally attained.
 - (f) Design factors.
 - (g) Speed factors expressed as an equation.
 - (h) Numerical example.
- 10. MOTOR SPEED CONTROL:**
 - (a) Applied e.m.f.
 - (b) Field strength.

11. SPEED REGULATION:

- (a) Definition.
- (b) Speed regulation expressed as an equation.
- (c) Numerical example.

12. POWER OUTPUT OF MOTOR:

- (a) Determining factors.
- (b) Output expressed as an equation.
- (c) Numerical example.
- (d) How measured.

13. POWER INPUT:

- (a) Determining factors.
- (b) Electrical input expressed as an equation.
- (c) Numerical example.

14. LOSSES IN MOTOR.

15. EFFICIENCY OF MOTOR:

- (a) Definition.
- (b) How determined:
 - (1) Directly.
 - (2) Indirectly.

16. ARMATURE REACTION IN MOTOR.

17. CONDITIONS FOR SPARKLESS COMMUTATION.

18. CLASSIFICATION OF MOTORS:

- (a) Shunt.
- (b) Series.
- (c) Compound:
 - (1) Differential.
 - (2) Cumulative.

19. MOTOR CHARACTERISTICS:

- (a) Shunt:
 - (1) Speed characteristic.
 - (2) Torque characteristic.
- (b) Series:
 - (1) Speed characteristic.
 - (2) Torque characteristic.
- (c) Differential compound:
 - (1) Speed characteristic.
 - (2) Torque characteristic.

(d) Cumulative compound:

- (1) Speed characteristic.
- (2) Torque characteristic.

20. MOTOR APPLICATIONS:

- (a) Shunt.
- (b) Series.
- (c) Differential.
- (d) Cumulative.

21. SHUNT MOTOR OPERATION:

- (a) Starting.
- (b) Speed variation.
 - (1) Field strength.
 - (2) Applied e.m.f.
- (c) Operating and controlling.

22. SERIES MOTOR OPERATION:

- (a) Starting.
- (b) Speed variation:
 - (1) Field strength.
 - (2) Applied e.m.f.
- (c) Operating and controlling.

23. COMPOUND MOTOR OPERATION.

24. MOTOR PROTECTIVE DEVICES.

25. MOTOR TROUBLES:

- (a) Sparking, heating, etc.
- (b) Excessive speed.
- (c) Under-speed.
- (d) Failure to start.

26. MOTOR TESTS.

27. LIMITATION OF OUTPUT.

28. RATING OF MOTORS.

LESSON 8 — THE DIRECT-CURRENT MOTOR

1. Definition of a Motor

A motor is a device for transforming electrical energy into mechanical energy.

2. Fundamental Principle of Motor

Maxwell's Law of Motor Action (see Lesson 3 — "Electromagnetic Laws") is the basic principle of the motor. According to this law, a coil of wire, which carries an electrical current, and which is free to rotate, will turn into such a position that it will enclose maximum flux, and all in the same direction. In other words, if a coil of wire were suspended in a magnetic field, as shown in Fig. 64, and free to rotate about its center, it would turn until it was at right angles to the magnetic field, thus enclosing the maximum number of lines of force. Since a large number of coils are uniformly distributed about the armature, in the practical motor, the rotation is continuous, for each coil follows the same law.

(a) *Motor action is Magnetic action.* The force which causes a current-carrying coil to rotate in a magnetic field is that due to the magnetic action between the main magnetic field and the field interlinked with the current. This is clearly shown in Fig. 64. The current is flowing outward on the left-hand side of the coil and hence the flux due to this current is in a counter-clockwise direction. It can be seen that this flux combines with the main flux beneath

the conductor and opposes the main flux above. Hence there is a strengthening of the field below this side of the coil and a weakening above it. The magnetic action therefore tends to push this side of the coil upwards. In like manner, current is flowing inwards, in the side to the right. Here

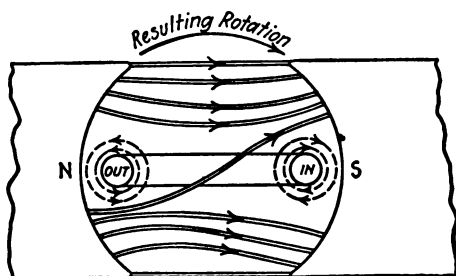


FIG. 64. — Illustration of the fact that motor action is magnetic action. The magnetic action between the main magnetic field and the field interlinked with the armature current causes the current-carrying coil to rotate in the magnetic field.

the magnetic field due to the current is in a clockwise direction. This field combines with the main field above the conductor and opposes it below. The resulting magnetic force acts downward upon this side.

Hence, since the coil is free to rotate, the magnetic force, pushing upward on the left side and downward on the right side, will rotate it in a clockwise direction. If the direction of the current in the coil is changed, or if the direction of the magnetism is reversed, the interaction between the two magnetic fields will be reversed, and hence the direction of rotation will be counter-clockwise. However, if both the direction of the current and of the magnetic field are reversed at the same time, there will be no relative change as far as the interaction between the two magnetic fields is concerned and hence there will be no change in the direction of rotation.

(b) *Generator as Motor.* Direct-current generators can be used, in practically all cases, as motors with very slight changes. If a closed coil is rotated in a magnetic field, so as

to cut lines of force, an e.m.f. is induced and current flows. The direction of this current depends upon the direction of the field and the direction of rotation (as explained under "Generators"). Moreover, according to Lenz's Law, a magnetic force will act on the coil, due to the interaction between the main field and that interlinked with the induced current, in such a way as to oppose further motion. In order to study the action of such a generator, when used as a motor, assume that an external source of e.m.f. is connected to the coil, in such a way that a current will be sent through it in the same direction as that of the induced current when it was used as a generator. Also assume that the direction of the magnetic field is the same and that the coil is free to rotate. Since the current is in the same direction, and the field is in the same direction, as in the case of the generator, the magnetic force acting will also be in the same direction. But, in the case of the motor, there will be no external force applied to overcome the magnetic force, and hence the magnetic force will cause rotation. Therefore this rotation will be opposite in direction to the case of the generator.

(c) *Generator Action in Motor.* By generator action, is meant the inducing of an e.m.f. An e.m.f. will always be induced in a conductor which cuts lines of force, and the motor is no exception to this rule. Despite the fact that current is flowing in the armature coils of the motor, due to the action of an external e.m.f., there will be another e.m.f. induced in these coils because they are cutting lines of force. This induced e.m.f. will be opposite in direction to the applied or external e.m.f. For this reason, it is usually referred to as "Counter e.m.f." The direction of the counter

e.m.f. can be verified by the right-hand rule. As an illustration, again take the case of the generator, used as a motor. It has been shown in (b) that with the same direction of magnetic field, and same direction of current in the armature coils, the direction of rotation in the motor will be opposite from that in the generator. It naturally follows that if the direction of rotation is reversed, the e.m.f. induced in the case of the motor (counter e.m.f.) will be opposite in direction to that induced in the generator.

3. Essentials of all Direct-Current Motors

These are exactly the same as those given for Direct-current Generators.

4. Construction of Motor

The construction of the direct-current motor is practically the same as that of the generator. (Described in Lesson 7.) However, since motors are used for nearly every purpose where a mechanical turning effort can be applied, it follows that there will be some variation in the minor constructional details. This especially applies to the degree of enclosure or protection. Thus the type of use may require that certain machines be "flame-proof," or "moisture-proof"; others may have to be "protected" from mechanical injury, while still others may be "open," with no restriction to ventilation other than that necessitated by considerations of sound mechanical construction.

5. Action of Commutator

Direct current is supplied to the commutator from an external source, through the brushes. The rotation of the

commutator reverses the direction of the current in the coils (since the commutator is simply a mechanical reversing switch) whenever they pass from one pole to another. As a result, the magnetic action is always maintained in one direction (since the current direction is reversed simultaneously with the field), and hence the rotation continues in the same direction. If it were not for the commutator, a current-carrying coil would be forced in one direction when under a north pole and (with same direction of current), in the reverse direction, when under a south pole.

6. Use of Multi-coils

If only one coil were used on the armature, the motor action would turn it until it enclosed the maximum number of lines of force (i.e. — until it assumed a direction at right angles to the flux) and thereafter, there would be no further tendency to rotate. By placing another coil at right angles to the first, the second coil would be receiving the maximum magnetic impulse when the first one arrived at dead-centre. However, even with two coils, the action would be jumpy. In order to obtain a smooth and uniform magnetic impulse and a resulting even speed of rotation, a large number of coils, equally spaced around the armature core must be used. The idea is analogous to the use of a number of cylinders in an automobile engine rather than only two, and with cranks equally spaced about the shaft. Instead of the turning force being applied in jerks, there is a smooth application of power, resulting in uniform speed of rotation.

7. Factors Determining Amount of Magnetic Force Exerted

(a) *Armature Current.* The greater the armature current, the stronger the field interlinked with it, and hence the greater the magnetic force exerted. When the motor is at rest, the armature current depends upon the applied e.m.f. and upon the resistance of the armature. When the armature is rotating, however, there is an additional factor to be considered. This is the counter or back e.m.f., which is induced in the armature winding, as explained above. The counter e.m.f. acts like a resistance to prevent flow of current in the armature. The greater the counter e.m.f., the less the armature current, and hence with other factors constant, the less the magnetic force exerted. Since the counter e.m.f. is of the same nature as any other induced e.m.f., its value will depend upon the field strength, the speed with which the field is cut, and the length of the conductor cutting the field. Thus, if the motor is slowed down by some external force, the speed of cutting is reduced, and with other factors constant, the counter e.m.f. is reduced. This, then, allows increased armature current to flow and there will be a resulting increase of magnetic force exerted. If the magnetic field is reduced or weakened there is a tendency for the counter e.m.f. to be reduced, but in this case, the reduction is only momentary, for the increased armature current causes an increased magnetic force to be exerted, and this increases the speed (provided there has been no change in the external resisting force), until the counter e.m.f. is again at its original value.

(b) *Field Strength.* The greater the strength of the magnetic

field, the greater the magnetic force exerted. Certain classes of motors are designed for constant field strength, while in others the field strength varies with the load. In general, armature reaction tends to weaken the field of all motors with increased load

(c) *Length of Conductor.* The longer the conductor in the field, at right angles to it, the greater the amount of magnetic force exerted. In other words, the more coil sides there are on the armature of the motor, the greater will be the amount of magnetic force exerted. The manner in which these coils are connected will modify this, to a certain extent, since the more armature paths there are between brushes the less will be the force exerted. Thus in a four-pole machine, a wave-wound armature (which has only two armature paths between the brushes) will have twice the magnetic force exerted on it that a similar lap-wound armature will have, since the lap winding in this case will have four armature paths between brushes. Of course, these conditions are constant for any given motor.

8. Motor Torque

(a) *Definition.* Torque may be described as turning effort. In a motor it is the product of the magnetic force applied to produce rotation, by the radius through which this rotation takes place. Thus the torque which a motor is able to develop will depend upon those factors which determine the amount of magnetic force exerted.

(b) *Unit of measurement.* Torque may be measured in "pounds-feet," since it is a measure of the force (in pounds) acting at right angle to a radius (in feet). The force produces or tends to produce rotation through this

radius. It is sometimes convenient to measure motor torque by the product of the pull, in pounds, on the belt at the circumference of the motor pulley, by the radius of the pulley, in feet. Thus, if the pull on the belt is 100 pounds, and the radius is $\frac{1}{2}$ foot, the motor torque is 50 pounds-feet.

(c) *Torque determined by Counter-torque.* When a motor is rotating with a constant velocity, the torque it develops is opposed by an equal and opposite counter-torque. This counter-torque is due mainly to the opposition which the mechanical load offers to being rotated. However, a small portion of the counter-torque is due to the friction and iron losses in the motor itself. When a motor is starting up or is speeding up, it must develop a torque greater than the counter-torque of the load, in order to accelerate. When it is being stopped, or when it slows down, the torque it develops is less than the counter-torque. Neglecting losses, the tendency in a motor, which has an e.m.f. applied to it, is for the torque to balance the counter-torque. In other words, the motor tends to exert a turning effort sufficient to turn over the load. With a heavy load, large motor torque is necessary, and hence, for a given constant field, large current must flow in order to develop the required amount of magnetic force. The current flow is regulated automatically by the counter e.m.f., which in turn depends upon the speed (if the flux and other factors are constant). Thus, if the load is increased, the counter-torque will momentarily overbalance the torque, thus causing the motor to slow down slightly. This will result in a reduction of the counter e.m.f. More current will then flow in the armature, until the torque increases sufficiently to take care of the load. It should be noted that a relatively small

decrease of speed, and consequently of counter e.m.f., will cause a very large increase of armature current and hence of torque. If the load or counter-torque is decreased (with field strength constant), there will be a momentary excess of motor torque, which will cause a slight increase of speed. This will result in a slightly higher counter e.m.f., which will cut down the armature current and hence the torque, until a balance is again obtained. The balance is thus automatically maintained between torque and counter-torque.

(d) *Torque independent of Speed.* For any given current, motor torque is independent of the speed. Thus, no matter whether the motor speeds up or slows down, so long as the armature current remains the same, and with constant magnetic field, the motor torque will be constant. Although it is usual for the armature current to vary with the speed, on account of the change in counter e.m.f., it is possible, by special means, to keep the armature current constant, even though the speed is changing.

(e) *Torque and Power.* The power output of a motor depends upon the product of its torque by its angular velocity or speed. Hence the torque of a constant speed motor may be used as a measure of its power.

(f) *Torque expressed as an equation.* The factors which determine the torque developed by a motor may be expressed as an equation, thus:

Torque (in pounds-feet)

$$= \text{Armature Current (in amps.)} \times \text{Number of Poles} \\ \times \text{Flux per Pole (in maxwells)} \times \text{Number of Active} \\ \text{Armature Conductors}$$

$$\text{All Divided by } 852,180,000 \times \text{Armature Paths between Brushes} \dots \dots \dots \text{Equation (25)}$$

(g) *Numerical example.* To determine the torque in pounds-feet which a 4 pole motor is exerting, when the armature current equals 40 amperes.

The following data is given:

Flux per Pole = 200,000 lines.

Number of Armature Coils = 120; hence number of active conductors = 240.

The armature winding is a wave winding; hence there are only two armature paths between brushes.

From equation (25):

$$\text{Torque} = \frac{40 \times 4 \times 200,000 \times 240}{852,180,000 \times 2} = 4.5 \text{ Pounds-feet.}$$

9. Factors Determining Motor Speed

(a) *For constant speed, torque must balance counter-torque.*

As explained above the motor torque must balance the counter-torque, in order to get constant speed.

(b) *Torque developed by means of armature current.* With other conditions constant (such as field strength, number and type of connection of armature conductors, applied voltage, etc.) the torque developed by the motor will be obtained through the agency of the armature current.

(c) *Armature current limited by counter e.m.f.* The current flowing in the armature will be determined by the applied e.m.f., the armature resistance, and the counter e.m.f. With the first two factors constant, the counter e.m.f. is the determining factor.

(d) *Counter e.m.f. limited by speed.* With the constant conditions as assumed above, the counter e.m.f. will increase with increased speed and will decrease with reduced speed. The armature current required to supply the necessary

motor torque will be determined by the counter e.m.f., and this latter will be automatically regulated by the speed. Of course, the governing factor will be the counter-torque. If this is momentarily greater than the motor torque, it will reduce the motor speed. If it is momentarily less, the motor speed will increase.

(e) *What determines speed finally attained.* The speed finally attained, under the given constant conditions, will be that speed which will give a counter e.m.f. just large enough to allow the required armature current to flow, necessary to furnish the torque to balance the counter-torque.

(f) *Design factors.* Variations in design will naturally affect the speed which a motor develops, under a given torque. Thus, an increased number of active armature conductors tends to increase the torque. Hence, for a given load, and substituting a motor with a larger number of armature conductors, smaller armature current will be required to supply the required torque. Reduction in armature current must be brought about through increased counter e.m.f. However, the increased number of active armature conductors increases the counter e.m.f. as well as the torque. Since a slight increase in counter e.m.f. results in a relatively great decrease in current, there is a tendency for too great a current decrease. This tendency is opposed by a decrease of speed, since in this case the balance between torque and counter-torque is reached at lower speed (due to the momentary decrease of motor torque). The speed decreases until the counter e.m.f. is again decreased to only a small amount more than its value in the case of fewer conductors. The speed is then such that the current required for a balancing torque flows in the

armature. The final result of a larger number of active armature conductors is a slower speed motor. In the above discussion, the increased resistance of the armature conductors, due to increased length, has not been considered, since its effect is negligible.

With two motors, having more than two poles, and of exactly the same design (same number of poles, etc.), one having a wave wound armature and one a lap wound armature, with the same applied e.m.f., and both used to turn the same kind of load, the lap wound motor will have a greater speed than the wave wound one. In general, it may be stated that the greater the number of armature paths between brushes, the greater will be the speed. The reason for this can be seen by considering the case of two four pole motors, of the same design, but one lap wound and one wave wound. The lap wound motor has four armature paths between brushes, while the wave wound machine has only two. Hence the wave wound armature has twice as many conductors in series, in this case, and this is equivalent to an increased length of the armature conductor, or in other words to an increased number of active armature conductors. It has been shown that an increased number of active armature conductors will give a slower speed motor, and hence the wave wound motor will have a slower speed than the lap wound one. Stated in another way, the greater the number of armature paths between brushes, the less conductors there are in series, and since this is equivalent to fewer active armature conductors, the greater will be the speed.

The effects of applied e.m.f. and field strength will be taken up in paragraph 10. Since the resistance of the ar-

mature is comparatively small, it is not an important factor in the determination of motor speed.

(g) *Speed factors expressed as an equation.* The various factors which determine the speed of a motor may be expressed as an equation, thus:

Speed (in Revolutions per minute)

$$= \left[\text{Applied E.M.F. (in volts)} - \text{Armature Current (in amps.)} \times \text{Armature Resistance (in ohms)} \right. \\ \left. \times 6,000,000,000 \times \text{No. of Armature Paths between Brushes} \right]$$

All Divided by Flux per Pole (in maxwells) $\times$ No. of Poles

$\times$ Number of Active Armature Conductors.

Equation (26)

(h) *Numerical example.* To determine the speed which a 4 pole, lap wound (4 armature path) 110 volt motor will develop, when supplying a torque of 40 pounds-feet.

The following data is given:

Flux per Pole = 1,000,000 maxwells.

Number of armature coils = 180, hence no. of active conductors equals 360.

Resistance of Armature Winding = 0.5 ohm.

Solving equation (25) for armature current:

$$\text{Armature Current} = \frac{852,180,000 \times 4 \times 40}{4 \times 1,000,000 \times 360} = 94.68 \text{ amps.}$$

From equation (26):

$$\text{Speed} = \frac{(110 - 94.68 \times .5) \times 6,000,000,000 \times 4}{1,000,000 \times 4 \times 360} \\ = 1045 \text{ R.P.M.}$$

(R.P.M. = revolutions per minute.)

10. Motor Speed Control

(a) *Applied e.m.f.* From the above discussion, it is clear that if the applied e.m.f. is increased (with flux and other conditions constant), the counter e.m.f. will also have to be increased, in order to limit the armature current to that required by the torque. Hence, this increase of counter e.m.f. must be brought about by an increase of speed. Variation of the applied e.m.f. thus offers a means of speed control.

(b) *Field strength.* An increased field tends to increase the torque. Hence, a smaller armature current is required to supply the needed torque. This must be brought about through increased counter e.m.f. However, the increased field increases the counter e.m.f. as well as the torque, and since a slight increase in counter e.m.f. results in a relatively great decrease in current, the armature current would be reduced below that value required by the torque to balance the counter-torque, were it not for the fact that the speed decreases. The speed drops until the counter e.m.f. is only slightly higher than its original value. The required current then flows in the armature. Hence, an increased field strength results in a slower speed.

In like manner, a weakened field reduces the torque, and also the counter e.m.f. Reduction of the latter results in a greater current flow in the armature. This is needed to supply the required torque. However, as mentioned above, when the field is weakened by but a small percentage, and the torque and counter e.m.f. likewise, there is a relatively great increase in the armature current. This tends to raise the torque above the required value. However, the speed

increases, thus raising the counter e.m.f. to nearly its former value, and in this way preventing too great an increase of armature current. Hence, the net result of weakening the field strength is to increase the speed of the motor.

This method of speed control is more commonly used than that mentioned under (a). The field strength is usually regulated by changing the field current, but in special motors it is sometimes regulated by changing the reluctance of the magnetic circuit.

11. Speed Regulation

(a) *Definition.* The "speed regulation" of a motor is its change of speed from full load to zero load, expressed as a percentage of the full load speed. Speed regulation has nothing to do with speed control, but is analogous to "voltage regulation" in a generator.

(b) *Speed regulation expressed as an equation:*

Speed Regulation (in %)

$$= \frac{\text{No Load R.P.M.} - \text{Full Load R.P.M.}}{\text{Full Load R.P.M.}} \times 100.$$

Equation (27)

(R.P.M. = revolutions per minute.)

The right-hand side of the equation is multiplied by 100 to get the speed regulation in "per cent."

(c) *Numerical example.* To determine the percentage speed regulation of a motor whose no load speed is 1500 and whose full load speed is 1400 R.P.M.

From equation (27):

$$\text{Speed Regulation} = \frac{1500 - 1400}{1400} \times 100 = 7.1 + \%.$$

12. Power Output of Motor

(a) *Determining factors.* The horse power output of a motor is proportional to the product of its torque and its speed. It has been shown above how torque is governed by counter-torque, and also how various factors affect the final speed attained.

(b) *Output expressed as an equation.* The horse power output of a motor may be expressed as an equation, in terms of the torque and speed, thus:

$$\text{Horse Power Output} = \text{Torque (in pounds-feet)} \times \text{Speed (in R.P.M.)} \times 0.00019403 \dots \text{Equation (28)}$$

From equation (7), 746 watts = 1 horse power. Hence, the output of a motor may be expressed in kilowatts by dividing equation (28) by 1000 and multiplying by 746. The following equation will then be obtained:

Kilowatt Output

$$= \text{Torque (in pounds-feet)} \times \text{Speed (in R.P.M.)} \times 0.00014474 \dots \text{Equation (29)}$$

(c) *Numerical example.* To determine the horse power output and the kilowatt output of a motor which is exerting a torque of 50 pounds-feet, while rotating at a speed of 1000 R.P.M.

From equation (28):

$$\text{Horse power Output} = 50 \times 1000 \times .00019403 = 9.7 \text{ Hp.}$$

From equation (29):

$$\begin{aligned} \text{Kilowatt Output} &= 50 \times 1000 \times .00014474 \\ &= 7.2 + \text{Kw.} \end{aligned}$$

(d) *How measured.* The horse power output of a motor is usually obtained by measuring the torque exerted, by means

of a Prony brake, and the speed by means of a stop watch and revolution counter. An instrument called a "tachometer" combines both the stop watch and the revolution counter, and hence is more convenient. However, it should be carefully calibrated and checked up before use, as it is subject to considerable error.

13. Power Input

(a) *Determining factors.* It has been shown, under "Laws of Electrical Power," that electrical power in watts = voltage times amperage. (See equation (4).) Hence the electrical power input into a motor will equal the e.m.f. impressed or applied at the motor terminals times the current being drawn by the motor.

(b) *Electrical input expressed as an equation.* The power input to a motor may be expressed in kilowatts, as follows:

Kilowatt Input

$$= \frac{\text{E.M.F. (in volts) Applied} \times \text{Current (in amps.) Drawn}}{1000}$$

Equation (30)

Equation (30) may be expressed in horse power by dividing by 0.746 or by multiplying by 1.34.

(c) *Numerical example.* To determine the power input, in kw. and in hp., when a motor is drawing 100 amperes from the line, if the voltage applied at the motor terminals = 220:

From equation (30):

$$\text{Power Input} = \frac{220 \times 100}{1000} = 22 \text{ Kilowatts.}$$

The Horse power Input = $22 \times 1.34 = 29.48 \text{ Hp.}$

14. Losses in Motor

These losses are the same as those of the generator. They consist of stray power losses and copper losses. (See paragraph 12, Lesson 7.) The greater the losses of a motor, the greater will be the input required for the same power output. In other words increased losses result in decreased efficiency. Since the electrical energy consumed in losses is finally converted to heat, increased losses also mean increased heating. The stray power losses reduce the useful torque.

15. Efficiency of Motor

(a) *Definition.* The efficiency of a motor is the ratio of its useful power output to its total power input. Since the efficiency is usually expressed in per cent this ratio must be multiplied by 100 to get it in these terms. The efficiencies of commercial motors range from 75 to 95 per cent.

(b) *How determined:*

(1) *Directly.* Motor efficiency may be determined directly by measuring the power output and the electrical input. The torque is measured by means of a Prony brake and the revolutions per minute are obtained and the power output is then calculated according to equation (29). The terminal voltage is measured by a voltmeter and the current drawn is measured by an ammeter in series with the motor and the line. The power input is then calculated according to equation (30). The percentage efficiency may then be obtained from the following equation:

$$\text{Efficiency (in \%)} = \frac{\text{Kilowatt Output}}{\text{Kilowatt Input}} \times 100.$$

Equation (31)

Numerical Example. To determine the efficiency of a motor whose output is 8 kw. and whose input is 10 kw. From equation (31):

$$\text{Efficiency} = \frac{8}{10} \times 100 = 80\%.$$

(2) *Indirectly.* Motor Efficiency may be determined indirectly by measuring the losses and by calculation from the following equation:

$$\text{Efficiency} = \frac{\text{Input} - \text{Losses}}{\text{Input}} \dots\dots\dots \text{Equation (32)}$$

The method of obtaining the losses is exactly the same as that explained in Lesson 7 — par. 13 (b) (2). The copper losses are calculated, while the various stray power losses are determined together by running the motor unloaded at rated speed. In this case the input, as obtained by the voltmeter and ammeter, is equal to the stray power losses. These losses are fairly constant under varying load, provided that the per cent speed regulation is low. The input may be calculated from the equation (30), measuring the voltage and amperage as in (1).

The various opposition methods, described under “Electrical Generators,” are also used to determine efficiency of motors.

16. Armature Reaction in Motor

Armature reaction is the effect of armature flux upon field flux. (For detailed explanation see Lesson 7 — par. 14, since the principle is the same for motors as for generators.) It should be noted that in a motor having the same direction of rotation as a generator, the current flowing in the armature will have to be in the reverse direction. (See par. 2

(b) above.) Hence, since the direction in which the flux is shifted, depends upon the direction of the main field and that of the armature field, it follows that in a motor, the direction in which the field is shifted, due to armature reaction, is opposite to that of the generator. In other words, the effect of armature reaction in a motor is to distort the field, and to shift the flux *back* against the direction of rotation. Hence the load neutral plane is back of the no load neutral plane. In general, the methods used for reducing armature reaction in a generator are applicable to the motor. However, several of these, such as "Eccentric Pole Shoes," can only be used where the rotation of the motor is always in the same direction.

17. The Conditions for Sparkless Commutation in the Motor Are the Same as those for the Generator

The effects of armature reaction and self-induction must be overcome. Although shifting the brushes backward against the direction of rotation, with increased load, will stop the sparking, there are a number of reasons why this method is undesirable for motors. In a motor, if the brushes are shifted against the direction of rotation, the field will be weakened. This will result in an increase of speed. Moreover, if the direction of rotation of the motor were reversed, the brushes would be in the wrong position. Brush shifting is never used for speed control because of the sparking which would result. Interpoles furnish the best means of obtaining sparkless commutation. Resistance commutation is always used in conjunction with the interpoles. In special motors compensating windings are used also. The position of the brushes is fixed in interpole motors. Since the inter-

pole windings are connected in series with the armature and the load, the direction of the interpole flux will reverse when the armature current is reversed. Hence, by reversing the armature current, to reverse the direction of rotation, the interpole flux will always be of the correct polarity. In a motor, the polarity of the interpole should always be the same as that of the pole just passed. Thus, if the rotation is from a north to a south pole, the interpole between must have a north polarity. Interpoles are especially useful in motors subject to frequent reversal, in variable speed motors, and in motors whose load is fluctuating.

18. Classification of Motors

All motors receive their field excitation from an external source. They may be classified according to the manner in which their field windings are connected:

(a) *Shunt*. In the shunt motor, the field winding is connected in parallel with the brushes (that is with the armature winding). If the current is reversed at the terminals, it will reverse in the field winding as well as the armature, and since there has been no relative change between them, there will be no change in the direction of rotation. Hence, in order to reverse the direction of rotation of a shunt motor, it is necessary to reverse either the armature current or the field, but never both. In a shunt interpole motor, it would be necessary to reverse the armature current for the reason given in paragraph 17. If a shunt generator were run as a motor, and with the same direction of current in the armature winding, the direction of the field current would be opposite to what it was in the case of the generator. If the generator was being rotated in a clockwise direction, then

under the conditions given above, the motor will also rotate in a clockwise direction. Although the motor action is always opposite to the direction of turning force exerted in a generator, it should be noted that in this case, the direction of the field has been reversed, thus causing a relative change in direction between main field and armature field. On this account, the direction of rotation remains the same in the generator and the motor when the armature current is in the same direction (provided the field connection is unchanged).

(b) *Series*. In the series motor, the field winding is connected in series with the armature winding and the line. If the current is reversed at the terminals, it will reverse in the field winding as well as in the armature and there will be no change in the direction of rotation. Hence, as in the shunt motor, in order to reverse the direction of rotation, it is necessary to reverse either the armature current or the field, but never both together. If a series generator were run as a motor, and with the same direction of current in the armature winding, the direction of the field current would be the same as in the case of the generator (since the field is in series with the armature). If the generator was being rotated in a clockwise direction, then under the conditions given, the motor would rotate in a counter-clockwise direction. This is in accordance with paragraph 2 (b). In the case of the series generator, acting as a motor, there is no change in the relative direction of the armature current and the field current.

(c) *Compound*. Compound motors have a shunt winding in parallel with the brushes and a series winding in series with the armature and the line. When a compound generator

is run as a motor, its direction of rotation will depend on the relative strength of the two fields. If the shunt field is stronger, its direction of rotation will be the same as that of the generator. If its series field is stronger, its direction of rotation will be opposite to that of the generator. (This assumes direction of armature current the same for each case.) Compound motors may be further classified as:

(1) *Differential*. A differentially compounded motor is one in which the series field winding is so connected as to oppose the shunt field. Thus if the direction of the series winding is such as to tend to make a north pole, the current direction of the series winding will tend to produce a south pole. The result is that while one winding (the stronger) magnetizes, the other one tends to demagnetize. The purpose of the differential winding will be taken up later.

(2) *Cumulative*. A cumulatively compounded motor is one in which the series field aids the shunt field. This combination gives some of the advantages of a series motor, without its disadvantage of racing at no load.

19. Motor Characteristics

(a) *Shunt*:

(1) *Speed characteristic*. The speed of the shunt motor is practically constant, but falls to a slight extent as the load is increased. This is shown by the curve in Fig. 65. The applied e.m.f. is assumed constant. The drop in speed may be only one or two per cent, between no load and full load, for large motors, while for small ones it may be as high as 15 %. At no load the speed of a shunt motor is such that the counter e.m.f. induced in the ar-

mature windings will practically equal the applied e.m.f. As the load is increased, more current is required to supply the necessary torque and this is obtained through a slight decrease of speed. A slight decrease of speed and hence of counter e.m.f. permits a relatively large current to flow. As increased current is drawn, armature reaction will be increased and this will tend to weaken the field. As explained above, when the field is weakened, the motor tends to speed up. Hence the armature reaction opposes the effect of increased current, and the net result is that the speed decrease is less than if armature reaction were not present. Of course, if not for armature reaction, the field strength would be constant so long as the applied voltage and the field resistance remained constant. As a matter of fact, the applied voltage is often subject to variation, while the resistance of the field winding increases as the motor becomes hot. Increased resistance of the winding results in less field current and a weakened field, thus tending to increase the speed. If the field excitation is such that the magnet cores are worked above saturation, the field strength will remain constant in spite of slight changes in the field current and also in spite of armature reaction. In this case the speed will be directly proportional to the applied voltage, and if this is kept constant, the speed regulation will be somewhat poorer than if the effects of armature reaction were present. If the magnetic circuit of the motor is worked at a point quite a good bit below saturation, there will be very little variation of speed, even though the applied voltage varies widely. This is because the field strength will vary directly with the field current in this case, and hence an in-

crease of applied voltage will increase the field strength. The tendency for an increased armature current will be opposed by an increase of counter e.m.f. (just as if the applied voltage increased with constant field), but in this case the increased counter e.m.f. will result from the strengthened field, instead of from an increase of speed.

(2) *Torque characteristic.* As the counter-torque on a shunt motor is increased, the torque which the motor

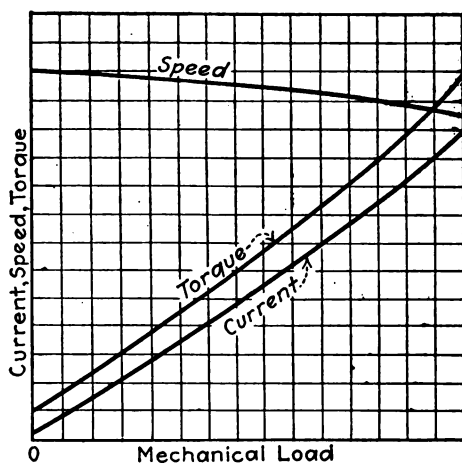


FIG. 65. — Shunt motor characteristic curves.

develops will increase and the armature current will also increase in almost direct proportion (Fig. 65). In other words, since the field is very nearly constant in the shunt motor, the necessary torque must be developed by means of the armature current. However, when the motor is heavily loaded, the field is weakened, as explained above, and hence the increase of current will not be in direct proportion, as comparatively more current will be required to supply the torque. Stated in another way,

more than double the current will be required to supply double torque, due to the weakening of the field with increased load.

(b) *Series:*

(1) *Speed characteristic* (Fig. 66). With the applied voltage constant, the greater the load, the less will be the speed of a series motor. As the load is lessened the motor will speed up, and if the load is entirely removed, it will

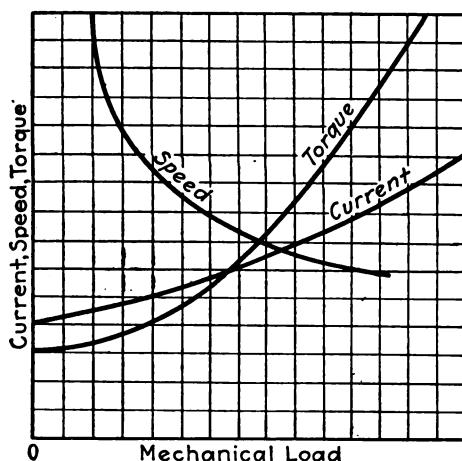


FIG. 66. — Series motor characteristic curves.

“run away.” In the series motor, increased torque necessary to counterbalance increased counter-torque is supplied by both increased armature current and increased field. When the load is increased, the motor slows down slightly, and the resulting decrease of counter e.m.f. allows more current to flow in the armature. Since the field is in series with the armature the field strength is increased as well as the armature current. This tends to slow the motor down still further (in accordance with paragraph 10

(b)). The speed finally reaches a constant value when the strength of the field and of the current in the armature is such as to supply the necessary torque. As the increased load decreases the speed, the tendency to decreased counter e.m.f. is opposed by the strengthened field. This prevents too great an increase of current.

As the counter-torque is decreased, the motor speeds up in order that the decrease of counter e.m.f. may limit the armature current to the required amount. However, since the armature and field are in series, the field is weakened also, and this results in a further increase of speed. This increase continues until a balance is once more attained. If the load is entirely removed, it is impossible to reach a balance, and the speed will continue to increase until the armature bursts, due to the action of centrifugal force upon it. Only a slight current is necessary to supply the torque to turn over the series motor at no load. With the load removed, the increased speed tends to increase the counter e.m.f. in order to limit the current flow to that required (to take care of losses). However, this tendency to increased counter e.m.f. is opposed by an ever weakening field, which pulls the counter e.m.f. down again. The speed increases more and more, and the field is further weakened, thus preventing the increase of the counter e.m.f. As a result, there will be sufficient current flow to continue the process until bursting speed is reached.

(2) *Torque characteristic* (Fig. 66). This is the most important characteristic of the series motor. Instead of varying directly with the current, as in the shunt motor, the torque increases with the square of the current. In

other words, if the current is doubled, the torque will be increased four times. If the current is tripled, the torque will be increased nine times. (This assumes the magnetic circuit worked considerably below saturation.) Hence, for the same current, the torque of the series motor will be much greater than that of the shunt. Moreover, the series motor will have a much better starting torque. The reason for the high torque of the series motor lies in the fact that the armature and the field are in series. Torque is proportional to field flux and to armature current. An increase of armature current in the series motor is accomplished by an increased field strength, since the current flowing in the armature also flows in the field winding. Hence doubled armature current also means doubled field (where worked well below saturation) and hence this results in quadrupled torque.

(c) *Differential compound:*

(1) *Speed characteristic* (Fig. 67). By proper design of the series winding, the speed characteristic of the series motor may be made such that an absolutely constant speed will be maintained at all loads. The weakening effect of the series field must be sufficient to counteract the tendency which a shunt excited motor would show, to slow down slightly at increased load. If the series field is too strong, the motor will speed up as the load is increased, due to the weakened field.

(2) *Torque characteristic.* Since there is a relatively large amount of current drawn at starting, the field will be greatly weakened at starting in a differential motor. Since the torque depends upon the field strength as well as the current, the starting torque of this motor will be

extremely poor. Moreover, if an attempt is made to overload the motor, the field will become greatly weakened, due to the action of the series winding, and as a result, the motor will be unable to develop the required torque. Hence it will stop, and the counter e.m.f. will fall to zero. The resulting rush of current will burn out the armature

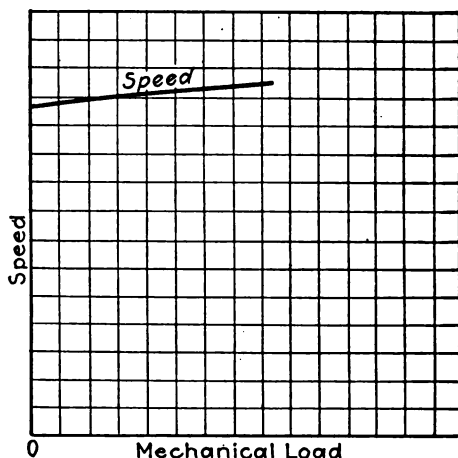


FIG. 67.—Speed characteristic of a differentially compounded motor.

unless it is protected by overload circuit breaker or fuses.

(d) *Cumulative compound:*

(1) *Speed characteristic* (Fig. 68). The speed of the cumulative motor decreases quite rapidly with increased load. This is because the series field, acting in the same direction as the shunt, increases the field strength as the load is increased. Hence the motor slows down to a greater extent than if it were simply shunt excited.

(2) *Torque characteristic* (Fig. 68). On account of the action of the series field, this motor has excellent starting

torque. Moreover, unlike the series motor, it will not “run away,” if the load is removed. Its torque, at all values of armature current, is much better than that of the shunt motor. In some cases, where the high starting torque is the principal consideration, the series field is short-circuited after full speed is attained.

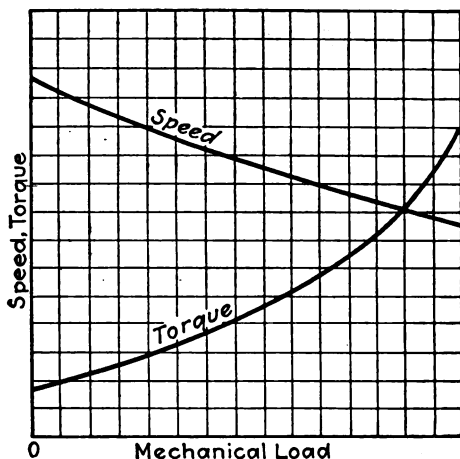


FIG. 68. — Speed and torque characteristic of a cumulatively compounded motor.

20. Motor Applications

- (a) *Shunt*. The shunt motor is adapted to loads requiring fairly constant speed, with moderate starting torque. Shunt motors find wide application in industrial work, for driving machine tools, line shafting, etc. They are also applied in cases where the load is liable to be entirely removed or where excessive speed would injure the machinery being turned.
- (b) *Series*. Series motors are adapted to loads requiring high starting torque and frequent stopping and starting. As the torque of the series motor is increased, the speed

decreases and this prevents excessive power consumption. The series motor is used for electric railway work, for hoists, etc.

(c) *Differential*. This motor is adapted only to special classes of work, on account of its poor torque characteristics. It is used where an absolutely constant speed is desired under varying load, but where the torque required is light. The motor in the motor generator set of commercial wireless telegraph outfits is an example of the use of differential compounding.

(d) *Cumulative*. The cumulative motor is adapted to loads which require high starting torque, with not too wide a variation of speed. Elevators and hoists are of this class. The motors used for such loads are heavily compounded (have a large number of series turns). In the case of elevator motors, the series field is short-circuited after constant running speed is reached. Where the load requires high starting torque and nearly constant speed, either the shunt field is heavily excited, or else the series field is cut out altogether after starting.

21. Shunt Motor Operation

(a) *Starting*. When the armature is at a standstill, there will be no counter e.m.f. induced, and hence there will be nothing to limit the current in the armature, except the armature resistance. Since this resistance is small, an excessive current would flow at starting, unless some external means were provided to limit the current flow. Hence, a starting resistance is always inserted in series with the armature and the line, and this is gradually cut out as the motor gets up to speed. The starting resistance is usually incorporated in

a starting box (Fig. 69). A form of starting box, which is often used, consists of the following essential features: resistance wire wound on porcelain insulators in coils, within a cast iron box; contact buttons on the face of the box, and connected to the resistance wire; a movable contact arm, which makes contact with the buttons and which can

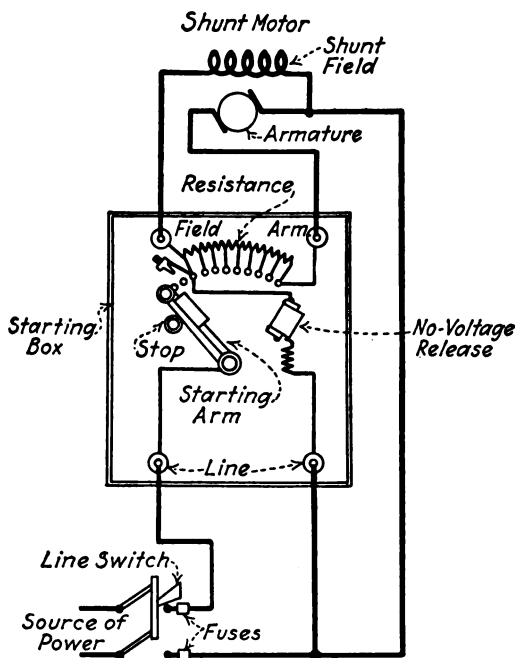


FIG. 69. — A shunt motor starting box.

be swung over until all the resistance is out of the circuit; a magnet, which holds the contact arm in position, with all the starting resistance cut out, but which is so connected that it releases the arm when there is no voltage in the line (hence called a no-voltage release); a spring to draw the arm into its original position, when released by the magnet,

and binding posts, or terminals for connecting the box properly to the motor and the line. In addition, some starting boxes are equipped with overload releases. These will be described later. As mentioned above, the starting resistance is connected between one of the motor terminals and one line terminal. The connections within the box are so arranged that as the contact arm is moved upward against the action of the spring, the starting resistance is gradually cut out of the circuit. The holding magnet is usually connected in series with the shunt field. It can then act both as a no-voltage release and as a no-field release. Where the holding magnet is connected directly across the line, it simply acts as a no-voltage release. A no-voltage release is necessary to allow the contact arm to return to its original position, and to automatically cut in the starting resistance, in case the voltage should suddenly go off the line. If the contact arm remained with the resistance entirely cut out in such a circumstance, and if the voltage should again be applied to the line, the resulting rush of current through the armature would probably burn it out. A no-field release provides against the motor "running away" in case of a break in the field circuit. A break in the field circuit reduces the field magnetism to the small amount furnished by the residual magnetism of the poles. This weak magnetic field is unable to furnish the required counter e.m.f., and hence the speed will become excessive unless the motor is disconnected from the line. However, with the field connected in series with the holding magnet, as in Fig. 69, the magnet will release the arm, in case the field circuit is broken, and the spring will then draw the arm back to its original position, thus disconnecting the motor.

One form of overload release consists of a magnet in series with the line and the armature. This magnet is arranged to attract a pivoted iron keeper if excessive current flows. The pivoted arm, when attracted by the magnet, makes connection between two contacts which are connected so as to short-circuit the holding magnet when the circuit is closed. Hence, if more than the allowable current is drawn from the line, the overload magnet attracts its pivoted keeper, and this closes the circuit whereby the holding magnet is short-circuited. The holding magnet then releases the contact arm and the spring pulls it back to its original position thus disconnecting the motor from the line. In another form of overload release, the overload release magnet attracts a pivoted arm, which is arranged so that this will result in breaking the circuit between the motor and the line. This then operates the no-voltage release.

In tracing out the connections of a starting box, it is well to bear the following points in mind: First, that the starting resistance must be in series with the armature and the line; second, that the shunt field connection must be such that the field will have full line voltage across it at starting, so that maximum starting torque will be obtained; third, that the usual connection of the holding magnet is in series with the field and the line; fourth, that a connection is practically always necessary between one motor terminal and the line, outside of the starting box. If two terminals are marked line, it is safe to assume that they should be connected to opposite sides of the line, since if both were supposed to be connected to the same side of the line, only one line terminal would be necessary on the box, and the other connection could be made within the box itself.

(b) *Speed variation:*

(1) *Field strength.* Variation of field strength is the usual method of changing the speed of shunt motors. The field current is varied by means of a rheostat connected in series with the field winding and the line. The more resistance in series with the field, the weaker will be the field excitation and hence the greater the speed. (See paragraph 10.) Shunt motors do not have a wide range of speed variation by this method, unless equipped with interpoles, since at speeds over 50 per cent above normal sparking will be objectionable, while it will be impossible to get speed very much below normal on account of the saturation of the field. Another method of varying the field strength, which requires a specially constructed motor, is by variation of the reluctance of the magnetic circuit. This is accomplished in certain motors by shifting the armature endwise, so that it will be moved a bit from the poles. Another way of varying the reluctance is by the use of hollow poles, fitted with movable cylindrical cores. When these are drawn outward, the length of the air gap is increased. The increase of speed which follows is not accompanied by the sparking associated with decrease of field current.

(2) *Applied e.m.f.* There are three distinct methods of varying the speed by variation of the applied e.m.f.

One method simply consists in inserting a resistance in series with the armature and the line. By varying this resistance, the e.m.f. applied at the terminals will also be varied. This method is extremely inefficient, because the load current must pass through the control resistance and hence the power loss (current squared times re-

sistance) will be excessive except at full speed. This method is not much used in practice, on account of its inefficiency.

Another method consists of the use of multi-voltages. In this method the control switch is arranged so that the motor can be connected across lines operated at different voltages. Thus, the motor may first be connected across a 60-volt line then across a 220-volt line, then across 440 volts, etc. Where a three-wire system or a three-wire generator supplies the energy, two voltages (usually about 120 and 240), one twice the other, will be very conveniently obtained. It is usual to supplement the multi-voltage method of speed control by the method first mentioned under (1).

A third method of speed change, depending upon variation of the applied e.m.f., is that known as the "Ward-Leonard System." This offers the most flexible means of motor speed control. An auxiliary motor generator set is necessary, the auxiliary motor being operated at a constant speed, and the auxiliary generator supplying the motor whose speed it is desired to control. This latter motor, although a shunt motor, has its field separately excited across the supply mains, instead of receiving its excitation from the auxiliary generator circuit. By changing the excitation of the auxiliary generator (by means of variable resistance in series with the field), any desired e.m.f. can be applied to the motor and hence practically any desired speed can be obtained. This system is chiefly used for the control of turret-turning and gun-elevating motors used on battle-ships. It is rather complicated and expensive for ordinary commercial work.

(c) *Operating and controlling.* Since the motor is also classed as a dynamo, it should be operated with the same care as the generator. Before starting, the motor should be carefully inspected to see that nothing has been left in the way to prevent rotation. The oil wells at the bearings should be filled. In addition to the starting box and means of speed variation described above, there are a number of special devices for controlling the operation of motors. These are called "motor controllers," or "speed regulators." These controllers usually combine the function of starting box and control switch for speed variation. In certain types, which vary the speed by variation of the applied e.m.f., the starting rheostat has sufficient carrying capacity to carry the load current continuously on any step. Thus, if the motor is started up, and the contact arm is left in mid-position, the resistance still in series with the armature cuts down the applied e.m.f. and hence the machine will operate at lower than normal speed. The controllers are equipped with no-voltage and overload releases similar to those used on starting boxes, except that the holding magnet will hold the arm in any point of contact along the controller resistance. Some controllers combine a field rheostat, for regulating the field strength, with the features of e.m.f. control, for further variation of speed.

In starting up a motor with the ordinary starting box, care should be taken to move the starting handle at a uniform speed, not too slow and not too fast. If moved too slow, there is a possibility of burning out some of the starting resistance as it is not designed to carry load current for any length of time. If moved too fast, the motor may not have a chance to come up to speed before full line voltage

is thrown on it, and in this case the counter e.m.f. will not be sufficient to prevent throwing the circuit breaker, or even burning out the fuses or the armature winding. There are a number of automatic motor starters on the market. When these are used, it is simply necessary to press a button in order to start the motor and bring it up to speed. In certain types of automatic starters, a solenoid cuts out successive resistances in series with the armature and the action takes place at a pre-determined uniform rate, thus eliminating the personal element.

While operating the motor, it should be frequently inspected, care being taken that the oil rings are rotating, that the oil cups and wells are sufficiently supplied with oil, and that the motor is not overspeeded.

To stop the motor, it is usually simply necessary to pull the line switch. The release magnet on the starting box, or controller, then allows the spring to pull the contact handle back into its original position. In certain special cases, where it is desired to bring the motor to rest rapidly, a device is provided which automatically short-circuits the motor terminals when the line switch is opened. The motor then acts as a short-circuited generator, and the large currents flowing produce sufficient magnetic drag, in conjunction with the field, to bring the motor to a quick stop.

The method of reversing a shunt motor is discussed in paragraph 18 (a). Where frequent reversal is necessary, a reversing switch is provided for reversing the current in the armature circuit without reversing the current in the field.

22. Series Motor Operation

(a) *Starting.* The series motor requires a starting resistance, just as the shunt motor does, to limit the current drawn at starting. The starting boxes for series motors are only slightly different from those used for shunt motors. In the type of starting box having two binding posts, the holding magnet is in series with the armature, the field, and the load. Hence, its excitation will vary with the load. In another type of box, the holding magnet is connected across the line.

(b) *Speed variation:*

(1) *Field strength.* The speed of a series motor may be changed by varying the field strength. This is accomplished by shunting the field winding with a variable resistance. This method is mainly applicable to interpole motors, since in motors without interpoles, variation of the field in this manner would cause sparking on account of the armature reaction.

(2) *Applied e.m.f.* There are, in general, two methods of varying the speed by variation of the applied e.m.f.:

One method consists of inserting resistance in series with the armature and the line, as in the case of the shunt motor. Although this method is used to a certain extent, still this is inefficient because of the energy consumed in the regulating resistance.

Another method of varying the applied voltage is to connect similar motors, first in series, and then directly across the line. In the former case, the applied voltage across each motor will be only one half that of the latter case. This method is used in conjunction with the use

of armature resistance in regulating the speed of street-railway motors.

(c) *Operating and controlling.* Series motors require the same general care as shunt and compound motors. In addition, there are certain precautions which apply only to the series motor. As mentioned above, series motors should never be started up without a load. It is preferable that series motors be permanently connected to the load. Where this is not feasible special precautions must be taken to prevent the motor from "running away" in case the load is accidentally thrown off.

In railway work, special controllers are used for operating and controlling the speed of the motors. These controllers are simply switches of the drum type. By turning the controller handle, the desired connections are made for starting and controlling the speed of the motors. In the case where there are two motors to the car, the first step of the controller connects the two motors in series and also in series with the starting resistance. As the controller handle is turned further, the resistance is cut out and the motors speed up. At the next step, the two motors are connected in parallel, but with a resistance between them and the line. Full speed is finally attained when further motion of the controller handle cuts out this resistance. Both motors now receive full line voltage.

The method of reversing the series motor is explained in paragraph 18 (b).

23. Compound Motor Operation

The starting, stopping, reversing, and speed control of the compound motor is accomplished in the same manner as

that of the shunt motor. Shunt motor starting boxes and regulators can be used for compound motors. However, special control devices are used for compound motors in cases where it is desired to cut the series winding out of the circuit after starting, etc.

24. Motor Protective Devices

Motors are usually protected by means of circuit breakers. These operate and open the line circuit as soon as the motor draws a certain predetermined current from the line. The overload release on the starting box performs the same function. As a further protection, fuses are usually connected on both sides of the line, and these burn out in case the circuit breaker fails to operate.

25. Motor Troubles

(a) *Sparking, heating, etc.* These are due to the same causes as mentioned under "Generators," and they can be prevented as explained under paragraph 19 of that heading.

(b) *Excessive speed.* This may be caused by too weak a field or by incorrect brush position. It can be remedied by cutting some of the resistance out of the field circuit, or by shifting the brushes to the position where least sparking occurs.

(c) *Under-speed.* This is generally due to an overload, but possibly may be due to overexcitation of the field. The remedy is obvious. Paragraphs (b) and (c) do not apply to series motors.

(d) *Failure to start.* This may be due to excessive load. In this case, the circuit breaker will probably trip or fuses may blow out. The load should be reduced and another attempt

made to start up. If the motor refuses to start, due to excessive friction, this can be determined by turning it over by hand. If there is bearing trouble, it will be very hard to turn it in this way. Open circuits, either in the machine itself or at the fuses, may be the cause of the trouble. First test for voltage at the terminals of the motor; then test for current in the armature by observing whether there is a spark when brushes are raised. The trouble may also be caused by short-circuits in the armature. Excessive current will then be drawn. If there is a short-circuit or "open" in the field, the machine will not start under load, and the magnetism will be weak. However, an open-circuit in the field of an unloaded shunt motor will cause it to "run away."

26. Motor Tests

The tests for "short-circuits," "grounds," "open-circuits," etc., are the same as those described in paragraph 20 under Generators.

27. Limitation of Output

The output of a motor is limited by the current-carrying capacity of its windings, sparking at the brushes, and its ventilation.

28. Rating of Motors

The rated power output of a motor is that load which it can carry continuously, without excessive sparking, and without exceeding certain temperature limits. The rating of the motor is usually stamped on the name-plate. It may be given in horse power or in kilowatts. The rated voltage is also stamped on the name-plate. The 220-volt motor is the one most commonly used for industrial work. The 110-volt motor is often used for light work.

APPENDIX
LABORATORY EXPERIMENTS

Outline of Appendix—LABORATORY EXPERIMENTS

- 1 — Calibration of Ammeter.**
- 2 — Calibration of Voltmeter.**
- 3 — Study of Direct-Current Ammeters and Voltmeters.**
- 4 — Study of Wattmeter.**
- 5 — Study of Watt-hour Meter.**
- 6 — Measurement of Resistance by Means of Wheatstone Bridge.**
- 7 — Voltmeter-Ammeter Method of Measuring Resistance.**
- 8 — Measurement of Resistance by Comparison of Voltmeter.
Deflections, using Standard Resistance.**
- 9 — Voltmeter Method for Insulation Resistance.**
- 10 — Measurement of Insulation Resistance — Direct Deflection
Method.**
- 11 — No-load Tests of Shunt Generator.**
- 12 — Load Characteristics of Shunt Generator.**
- 13 — No-Load and Load Tests of Series Generator.**
- 14 — Load Characteristics of compound Generator.**
- 15 — Operation of Shunt Generators in Parallel.**
- 16 — Compound Generators in Parallel.**
- 17 — Starting Boxes; No-Load Characteristics of Shunt Motor.**
- 18 — Shunt Motor Brake Test.**
- 19 — Brake Test of Series Motor.**
- 20 — Compound Motor.**

Experiment 1 — CALIBRATION OF AMMETER

- 1. Purpose.** To calibrate direct-current ammeter by comparison with ammeter of permanent magnet, movable coil type.
- 2. Apparatus.** Standard ammeter; ammeter to be calibrated; standard shunts for the required range of current; variable resistance; source of power.
- 3. Procedure.** Connect the ammeter to be calibrated in series with the standard instrument, the variable resistance and the source of power. Adjust the current value by means of the variable resistance so that a full scale reading can be taken. Take readings of both ammeters simultaneously. Reduce the current value by about 5 amperes; by means of the variable resistance, and take readings as before. Continue readings, every 5 amperes, until range of instruments has been covered.
- 4. Curves:**
 - (a) Plot standard amperes as ordinates — actual amperes as abscissae.
 - (b) Plot corrections necessary as ordinates — actual amperes as abscissae.
- 5. Answer in report:**
 - (a) Are instruments affected by being placed too close together? Why?
 - (b) What special precautions should be observed in using ammeters?
 - (c) Name several types of direct-current ammeters.

Experiment 2 — CALIBRATION OF VOLTMETER

1. **Purpose.** To calibrate direct-current voltmeter by comparison with voltmeter of permanent magnet, movable coil type.
2. **Apparatus.** Standard voltmeter; voltmeter to be calibrated; variable resistance; source of power.
3. **Procedure.** Connect variable resistance in series with source of power. Connect both voltmeters across same points of variable resistance, and so that they will indicate change when resistance is varied. If one resistance is not sufficient, use two in series. By varying resistance, take voltage readings, about every 5 volts over entire range of instrument.
4. **Curves.** Plot a correction curve so that for any actual reading of the voltmeter under test, it can be seen from the curve how many volts must be added or subtracted. Plot actual readings as abscissae — corrections as ordinates. Put positive corrections above the horizontal base line, negative corrections below.
5. **Answer in report:**
 - (a) What precautions are necessary in using voltmeters?
 - (b) Name several types of voltmeters. Which are most accurate?
 - (c) Why is a mirror placed beneath the pointer? How is it used?

Experiment 3 — STUDY OF DIRECT-CURRENT AMMETERS AND VOLTMETERS

1. **Purpose.** To study operating principles and construction of various types of direct-current ammeters and voltmeters.
2. **Apparatus.** Ammeters; voltmeters; stop watch; lamp bank; source of power.
3. **Procedure:**

- (a) Sketch roughly, in the laboratory, the important elements of each instrument.
- (b) Connect all the ammeters in series with the lamp bank and the source of power, and all the voltmeters in parallel with the lamp bank, and observe following, for each instrument: Whether instrument is dead-beat; whether affected by stray fields; whether affected by proximity of other instruments; whether adapted for portable use; how damping is obtained; whether scale is uniformly calibrated; what force returns pointer to zero.

Next test each instrument for zero. When it is placed in the position in which it is to be used, the pointer should be on zero. Note method provided for making zero adjustment, and perform this, if necessary. (Do this under instructor's personal supervision — never bend the needle.)

Test each instrument for balance. After the meter has been set on zero, test the balance by placing the meter in several different vertical positions. If properly balanced, pointer should not deviate more than one-sixteenth inch from zero.

Finally, test each instrument for sluggishness. Cause the needle to swing and note whether it comes back to the same point.

4. Answer in report:

- (a) Explain how changes of temperature affect accuracy of voltmeters and ammeters.
- (b) Explain how to use a voltmeter above its range. Below its range.
- (c) Name the various types of ammeters and voltmeters.
- (d) Explain differences between ammeters and voltmeters.
- (e) What will happen if an attempt is made to use an ammeter as a voltmeter?
- (f) What will happen if an ammeter marked "use with external shunt," is put in a circuit without a shunt?
- (g) Explain the use of various shunts to increase range of ammeter.

Experiment 4 — STUDY OF WATTMETER

- 1. **Purpose.** Study of connection and operation of indicating wattmeter, and calibration with reference to voltmeter and ammeter.
- 2. **Apparatus.** Wattmeter; ammeter; voltmeter; lamp bank for load; source of power.
- 3. **Procedure:**
 - (a) Connect the apparatus as shown in Fig. 33 (Lesson 5). Be sure before connecting, that the voltage range of the instrument is greater than that of the line. Turn on a single lamp in the lamp bank, and

alter connections so that all instruments read in the proper direction. Reverse the potential connections of the wattmeter, and explain change of deflection. Reverse the current connections. Explain change. Determine what will happen when both current and voltage connections are reversed. Explain.

- (b) With several lamps as a load, note the reading of the wattmeter in whatever position it happens to be in. Then shift it through 90 degrees in the same plane, and note any change in deflection. Finally shift it to a position at 180 degrees from its first position, and note any change. Reverse both current and voltage connections, noting change. Keep load constant during these tests. Tabulate results. Explain.
 - (c) Turn on more lamps, until wattmeter carries full rated current. Read volts, amps., and watts. Take about 10 sets of readings, gradually reducing current to zero. Keep the voltage constant throughout the test, and be sure to eliminate the effects of terrestrial magnetism. Shift connections so as to use "Ind" terminal, and take several readings using same current values as above. Note whether readings check with those obtained in first case, and explain any differences.
4. **Curves.** Calculate true watts by multiplying voltmeter readings times ammeter readings. Plot the actual watts recorded by wattmeter as abscissae; plot correction values as ordinates, placing watts to be added above the horizontal line, those to be subtracted below.

Thus, if the wattmeter reads 20 watts and the actual power is 15, then at the 20 watt point on the abscissa, it is necessary to plot an ordinate of 5 watts below the line, showing that to get the true power, it is necessary to subtract 5 watts.

5. Answer in report:

- (a) What is the purpose of the compensating coil?
- (b) If the " $\pm$ " and the "Ind" terminals were used as potential terminals, what would be the result?
- (c) How is it possible to make the scale uniform in this type of instrument?
- (d) Describe briefly the construction and the principle of operation of this type of wattmeter.

**Experiment 5 — STUDY OF WATT-HOUR
METER.**

- 1. **Purpose.** To study adjustment, calibration, and construction of commutator type watt-hour meter.
- 2. **Apparatus.** Commutator type watt-hour meter; lamp bank for load; voltmeter; ammeter; stop watch; source of power.
- 3. **Procedure:**
 - (a) Study the operating principle of the meter; sketch instrument, showing the proper method of connection to load and line.
 - (b) Connect up instruments as shown in Fig. 20 (a) (Lesson 4). Study the adjustment of the friction compensating coil. Determine the position of the coil at which the meter will creep; position at which meter will creep when jarred, and position at which

it just ceases to creep. Leave coil at this last position and determine power necessary to start.

- (c) Adjust the permanent magnets so that they give the correct constant (as marked on the rotating disc) at full load. The method of making this adjustment is as follows: Using the stop watch, count the number of whole revolutions of the disc, for about 60 seconds. At the same time, read the ammeter and the voltmeter. Then the volts, times the amperes, times the time in seconds will equal energy in watt-seconds. If this is divided by 3600 (since there are 3600 seconds in an hour) the actual watt-hours will be determined. This should check up with the product of the constant of the meter times the number of revolutions. Thus, suppose that the constant of the meter is 0.4. This means that 0.4 watt-hours are recorded for each revolution of the disc. Assume that the disc completed 15 revolutions in 30 seconds. Then the meter recorded $15 \times 0.4 = 6$ watt-hours. This should check up with the calculation of the actual watt-hours. If it is higher than the actual watt-hours, then the meter is going too fast, and the permanent magnets should be moved nearer the circumference. If it is lower than the actual watt-hours, the meter is going too slow, and the permanent magnets should be moved towards the center. In either case, the test must be performed again, until the recorded watt-hours, as obtained from the number of revolutions times the constant, check with the actual watt-hours.

(d) With the meter correctly adjusted, as per (b) and (c), vary the load from 5 per cent load to 100 per cent overload, taking readings as in (c), at suitable load intervals. Do not change the position of the permanent magnets or of the compensating coil.

4. Curves. Plot actual watt-hours recorded (as obtained from revolutions of disc, times constant marked on disc) as abscissae; plot correction values as ordinates, placing watt-hours to be added above the horizontal line, and those to be subtracted below the line. As an illustration, suppose that the true watt-hours, as obtained from the readings of the voltmeter, ammeter, and stop watch, to be 100, while the watt-hours as calculated, using the instrument constant, are 95. Then at this load, the meter is too slow, and it is necessary to add 5 watts to get a correct reading. Hence, at the 95 watt-hour point on the abscissa, it is necessary to plot an ordinate above the line, equal to 5 watts.

5. Answer in report:

- (a) What is the difference between power and energy?
- (b) How is the rotation of the watt-hour meter made proportional to the energy expended?
- (c) Why must friction be compensated for?
- (d) Explain how to read the meter dials.
- (e) If the compensating coil is moved nearer the armature, should the meter speed up or slow down?

Experiment 6 — MEASUREMENT OF RESISTANCE BY MEANS OF WHEATSTONE BRIDGE

1. **Purpose.** To study the operation of the Wheatstone bridge method of measuring resistance.
2. **Apparatus.** Several unknown resistances; three known variable resistances; galvanometer; several dry cells; galvanometer and battery key.
3. **Procedure:**

(a) Connect up the three known resistances and one unknown resistance in a closed circuit (as shown in Fig. 23 (Lesson 5)), also connecting galvanometer and battery as in this figure. Arrange the keys so that battery circuit will be closed first. Adjust the ratio arms so that their resistances are in multiples of 10. Referring again to Fig. 23, the ratio of arms 1 to 2 should be as follows (where rheostat arm has a total of 6000 ohms resistance):

For resist's up to	11 ohms make	Ratio arm 1 =	1;	arm 2 =	100
" res. from 11 to 100	" " "	" " =	10;	" " =	100
" res. " 100 to 1000	" " "	" " =	100;	" " =	1000
" res. " 1000 to 6000	" " "	" " =	1000;	" " =	10000
" res. " 6000 to 100,000	" " "	" " =	10000;	" " =	100000

In this last case, the positions of the unknown resistance and the rheostat arms must be interchanged. That is, the unknown resistance is now connected between *D* and *B*, and the variable resistance is connected between *C* and *B*. The same holds for all resistances above about 6000 ohms. For very high resistances make the ratio of arms 1 to 2, one

to one thousand. It should be noted that, with the unknown resistance at *DB*, the Wheatstone bridge equation becomes:

$$\text{Unknown resistance} = \frac{\text{Arm 2}}{\text{Arm 1}} \times \text{resistance of rheostat arm.}$$

If the approximate resistance of the unknown resistance is known, arrange the ratio arms in accordance with the above table, and adjust the rheostat arm until there is no deflection of the galvanometer when the keys are closed. The method to be followed is to try a rather large resistance in the rheostat arm, and note the direction of the galvanometer deflection; then try a small resistance and see whether the deflection is in the opposite direction. If it is, then the desired adjustment lies between the two values tried. By gradually reducing the high resistance, and increasing the low resistance, that value is finally determined, at which there is no deflection of the galvanometer. Calculate the value of the unknown resistance from the equations of the Wheatstone bridge. Take several readings as a check. Vary the ratio arms and again attempt to balance the bridge.

- (b) Determine the values of the other unknown resistances. Connect two resistances in parallel and determine the joint resistance. Connect the same two resistances in series and determine total resistance.

4. Answer in report:

- (a) Where is the Wheatstone bridge used?

- (b) What is meant by "zero method," and what are the advantages of this?
- (c) Calculate the joint resistance of the two resistances in parallel (as explained in "Electrical Circuits") and compare this result with that obtained by the Wheatstone bridge. Do the same thing with the resistances in series.

Experiment 7 — VOLTMETER-AMMETER METHOD OF MEASURING RESISTANCE

- 1. Purpose.** To study method of measuring resistance with voltmeter and ammeter.
- 2. Apparatus.** Ammeter; voltmeter; variable resistance; source of power.
- 3. Procedure.** Connect up the apparatus as in Fig. 26 (Lesson 5); if the resistance is rather low, and the line voltage is such that too high a current will flow when resistance is placed directly across the line, it will be necessary to place the variable resistance in series with the resistance to be measured. This especially applies to armature windings, series field windings, etc. In any case, it is safer to start with the variable resistance in the circuit.
 - (a) Determine the insulation resistance of a generator armature winding. Allow current equal in value to full load current to flow through the winding for about 15 minutes, in order to heat coil to operating conditions. Then read ammeter and voltmeter and calculate resistance as explained in

Lesson 5. Vary the current and take readings again. Do this several times and average up results.

- (b) Determine resistance of series winding of compound generator. Follow same method as in (a).
- (c) Determine resistance of shunt winding of compound generator.
- (d) Determine resistance of unknown resistances supplied by instructor.

4. Answer in report:

- (a) Where is the voltmeter-ammeter method generally used?
- (b) What are its advantages?
- (c) What is the best method of connection where the unknown resistance is low? What error is introduced in this connection?
- (d) What is the best method of connection where the unknown resistance is high? Where is the source of error in this case?

Experiment 8 — MEASUREMENT OF RESISTANCE BY COMPARISON OF VOLTMETER DEFLECTIONS, USING STANDARD RESISTANCE

1. **Purpose.** To study measurement of resistance by comparison of voltmeter deflections, using standard resistance. Also to determine influence of material, length, and cross-section of conductor upon its resistance.
2. **Apparatus.** Voltmeter; standard resistance; unknown resistances; dry cells or other source of power; yard stick; micrometer calipers or wire gauge.

3. Procedure. Connect resistance to be measured in series with a standard resistance, and a few dry cells. First connect voltmeter across standard resistance and record its deflection; then connect it across unknown resistance and again record deflection. Keep current constant.

- (a) Measure resistance of conductors furnished by instructor.
- (b) Repeat using one-half length and also double length of each conductor.
- (c) For this part of the experiment, conductors of three or four different materials are needed. Measure cross-sectional area of each conductor, using micrometer caliper or wire gauge to determine diameter. Measure length with yard stick, determining resistance by above method, of length measured.

4. Answer in report:

- (a) Calculate from data of (c), the "resistivity" of each conductor, in ohms per mil foot. (Use equation 19.)
- (b) Determine the materials of the conductors tested, by comparing their resistivity with that given for various conductors in E. E. Handbooks.
- (c) Explain fully theory of determining resistance by above method.
- (d) How does the resistance of a conductor vary with length? with cross-sectional area?

Experiment 9 — VOLTMETER METHOD FOR INSULATION RESISTANCE

- 1. Purpose.** To determine the use of the voltmeter in measuring insulation resistance.
- 2. Apparatus.** Voltmeter of known resistance and source of power.
- 3. Procedure.** Follow directions given in Lesson 5, paragraph (c) (see Figs. 27, 28, 29):
 - (a) Measure resistance of dead line, having one side grounded.
 - (b) Measure resistance of live line, having positive side grounded.
 - (c) Measure resistance between commutator and frame of generator.
 - (d) Measure resistance of human body.
- 4. Answer in report:**
 - (a) If the voltmeter shows no deflection when connected in series with the resistance to be measured, what does this indicate, with reference to the value of the unknown resistance?
 - (b) Where is this method used?
 - (c) Explain the theory of this method.

Experiment 10 — MEASUREMENT OF INSULATION RESISTANCE—DIRECT DEFLECTION METHOD

- 1. Purpose.** To determine the insulation resistance of an insulated wire coil.
- 2. Apparatus.** Sensitive galvanometers; Ayrton shunt; coil of insulated wire; jar for salt water; switches; source of power.

3. Procedure:

- (a) Determine constant of apparatus, connecting up as explained in Lesson 5, Fig. 30. Follow directions given in Lesson 5, under "Direct Deflection method for Insulation Resistance,"
- (b) Determine insulation resistance of the wire, following directions as in (a).

4. Answer in report:

- (a) If the insulation resistance of one-tenth mile of wire is 50 megohms, what is the insulation resistance of a mile of the same wire? Of a yard?
- (b) Explain the action of the wire guard.
- (c) Calculate the specific resistance, or resistivity of the tested sample, in ohms per mil foot (use equation 19, and data obtained from instructor).

Experiment 11 — NO-LOAD TESTS OF SHUNT GENERATOR

- 1. **Purpose.** To obtain no-load characteristics of direct-current shunt generator in order to study relation between exciting current and terminal voltage. Also to obtain speed-voltage characteristic.
- 2. **Apparatus.** Shunt generator; field ammeter; voltmeter; speed counter; stop watch; field rheostat; motor or prime mover to turn generator.
- 3. **Procedure:**
 - (a) Run generator at rated speed, keeping speed constant. Connect field ammeter and field rheostat in series with shunt field. Take readings of field amperes; terminal volts. Start readings with field

ammeter all "out," and gradually cut in field resistance in about equal steps, finally opening field circuit. With field amperes zero, read terminal volts.

- (b) With constant field excitation, increase the speed from lowest possible value to that speed specified by instructor, taking readings of terminal volts and speed, at suitable intervals.

4. Curves:

- (a) Plot data obtained in run (a):
Field amperes as abscissae; terminal volts as ordinates.
- (b) From data of run (b), plot:
Speed as abscissae; terminal volts as ordinates.

5. Answer in report:

- (a) What makes self-excitation of shunt generator possible? Explain.
- (b) Explain shape of curves obtained from runs (a) and (b).
- (c) What is meant by "saturation" of iron in the magnetic circuit?
- (d) If a run is taken as in 3 (a), but increasing field current instead of reducing, it will be found that the curve lies below that obtained in (a). What causes this?

Experiment 12 — LOAD CHARACTERISTICS OF SHUNT GENERATOR

- 1. Purpose. To determine load characteristics of shunt generator.

2. Apparatus. Shunt generator; field ammeter; load ammeter; voltmeter; field rheostat; speed counter; stop watch; lamp bank for load; motor or prime mover to turn generator.

3. Procedure:

- (a) Connect field ammeter in series with shunt field, load ammeter in series with armature and load. Load generator with lamp bank to about one and one-fourth full load. Adjust field rheostat to give rated voltage at this load. Keep rheostat at same adjustment throughout run and keep generator at rated speed. Read load amperes; field amperes; and terminal voltage. Reduce the load to zero in about ten equal steps taking readings at each step.
- (b) Make same run as in (a) and start with one and one-fourth full-load current but with field rheostat adjusted to give rated voltage at full load.
- (c) With field rheostat adjusted to give rated voltage at no load, gradually increase load until generator is short-circuited. Keep speed and field adjustment constant. Read load amperes, field amperes, and terminal volts. (This run should only be performed with small generator and under supervision of instructor.)

4. Curves:

- (a) Using data from run (a):
Plot load amperes as abscissae; terminal volts and field amperes as ordinates.
- (b) Using data from run (b) plot same values as abscissae and as ordinates as used in curve (a), plotting curves on same sheet.

- (c) On separate sheet, plot values obtained in run (c): Load amperes as abscissae; terminal volts and field amperes as ordinates.

5. Answer in report:

- (a) Name three reasons why voltage falls with increased load in the shunt generator.
- (b) Calculate the regulation of the generator from runs (a) and (b).
- (c) Will a shunt generator give better regulation when the iron is above or below saturation? Why?
- (d) Name the various losses in a generator.

**Experiment 13 — NO-LOAD AND LOAD
TESTS OF SERIES GENERATOR**

- 1. Purpose.** To study characteristics of series generator.
- 2. Apparatus.** Series generator; ammeter; load rheostat; voltmeter; stop watch; motor or prime mover to turn generator.
- 3. Procedure:**
 - (a) To obtain magnetization curve: For this test, the machine must be separately excited. Start with excitation current one and one-fourth times rated value. Run at constant rated speed. Read field amperes and terminal volts. Start readings at high value and reduce in about 10 equal steps to zero.
 - (b) To obtain external characteristic curve: Connect field in series with the armature. Connect voltmeter across both. Connect ammeter in series

with generator and load. Start at one and one-fourth rated load, take readings of ammeter and voltmeter at each step, reducing current in about 10 equal steps to zero.

- (c) Measure combined field and armature resistance by voltmeter-ammeter method.

4. Curves:

- (a) From data of run (a), plot magnetization curve. Amperes as abscissae; terminal volts as ordinates.
- (b) On same sheet, from data of run (b) plot external characteristic curve: Same abscissae; terminal volts as ordinates.
- (c) On same sheet, plot product of load current times combined field and armature resistance as ordinates; same abscissae.
- (d) Add values of curve (c) to curve (b) to obtain "internal" or total characteristic curve. The difference between curve (d) and (a) represents drop of voltage due to armature reaction.

5. Answer in report:

- (a) Explain special measures necessary to get series generator to build up.
- (b) Explain why variations in load, in above tests, must be continuous, without going back for readings.
- (c) Explain how the internal characteristic curve is derived from the external.
- (d) Why does the internal characteristic curve differ from the magnetization curve?
- (e) Explain why voltage increases with load current in series generator, and also what limits this increase.

Experiment 14 — LOAD CHARACTERISTICS OF COMPOUND GENERATOR

1. **Purpose.** To determine load characteristic of a compound generator.
2. **Apparatus.** Compound generator; load ammeter; field ammeter; voltmeter; speed counter; stop watch; field rheostat; lamp banks for load; motor or prime mover to turn generator.
3. **Procedure:**
 - (a) Connect generator cumulatively compounded and adjust field rheostat so as to get rated no-load voltage at rated speed. Gradually load the machine in about equal steps to one and one-fourth times rated current capacity (without altering position of field rheostat) and take readings at each step of field and armature currents, and terminal voltage. Keep speed constant.
 - (b) Connect generator so that it is differentially compounded and repeat readings as in (a).
 - (c) Connect machine as a shunt generator and again make a load test.
4. **Curves.** Plot load amperes as abscissae; field amperes and terminal volts as ordinates. Plot three sets of curves (from data of (a), (b), and (c)) on one sheet.
5. **Answer in Report:**
 - (a) How is it possible to tell whether generator is cumulatively or differentially compounded?
 - (b) What is the effect of shunting the series field of a cumulatively compounded generator?

- (c) Explain difference between "short shunt" and "long shunt" connection of compound generator.
- (d) Explain reason for difference of load characteristics of shunt, cumulative, and differential generators.
- (e) What three classes are cumulative generators divided into?
- (f) Where are over-compounded generators used? flat compounded?
- (g) Where are differentially compounded generators used?
- (h) What is meant by "voltage regulation" of a generator?

Experiment 15 — OPERATION OF SHUNT GENERATORS IN PARALLEL

1. **Purpose.** To study operation of shunt generators in parallel.
2. **Apparatus.** Two shunt generators; field rheostats; lamp banks for load; voltmeter; two load ammeters; speed counter; stop watch; motors or prime movers to turn generators.
3. **Procedure:**
 - (a) Connect each shunt generator through a double-pole, double-throw switch to common bus bars, and connect bus bars to load. Connect ammeter in series with each machine so as to read current supplied by that machine. Connect voltmeter so that it can be switched from terminals of one generator to those of the other. Be sure that

positive terminal of each machine connects to same bus bar (test with voltmeter). Bring each machine up to rated speed and adjust field rheostats so as to obtain rated voltage at no load. Connect one machine to bus bars and load to full load current by means of lamp bank. Practice throwing other generator in parallel. Try this with voltage of generator being thrown in exactly same as bus bar voltage; with voltage slightly higher than bus bar voltage; and with voltage slightly lower. Note which gives best results. Adjust field rheostats so that each machine bears its share of load.

- (b) Increase load on two generators in parallel until each machine is carrying its full rated load. Leave field rheostats set at point which gave rated voltage at no load. Keep speed constant at rated value. Take load run, reducing load in about equal steps from full load to zero load. Take readings of field amperes, load amperes for each machine, and bus bar voltage.
- (c) Make a load test of each generator separately under same conditions as in (b).
- (d) With two generators in parallel, and carrying a slight load, gradually weaken the field of one generator until the other one supplies current to it and runs it as a motor. Disconnect its driving motor from the line, so that its operation as a motor will be more apparent.

4. Curves:

- (a) From data obtained in run (b) plot total load

current as abscissae; bus bar volts, load amperes for each machine, as ordinates.

- (b) From data obtained from run (c) plot load amperes as abscissae; terminal volts of each machine as ordinates.

5. Answer in report:

- (a) What is the advantage of operating generators in parallel?
- (b) What about the characteristics of two shunt generators in order for them to automatically share all loads equally when in parallel?
- (c) If two shunt generators are connected in parallel and do not share the load equally, explain what adjustments must be made to make each take its share of the load.
- (d) Explain in detail how to connect one shunt generator in parallel with another one carrying a load.
- (e) Explain how to cut out a loaded shunt generator, which is operating in parallel with another.
- (f) Explain how it is possible for a generator to be run as a motor when operating in parallel with other machines.
- (g) What would happen if the positive terminal of a machine being connected in parallel were connected to the negative bus bar instead of to the positive?

**Experiment 16 — COMPOUND GENERATORS
IN PARALLEL**

- 1. Purpose.** To study operation of compound generators in parallel.

2. Apparatus. Two ammeters (0-100 range); two field ammeters (0-5 range); voltmeters; ammeter (0-50 range) for equalizer circuit; speed counter; stop watch; compound generators; motors or prime movers to turn generators.

3. Procedure:

- (a) Connect generators so that they are cumulatively compounded. Run each generator separately, getting "load characteristic," as explained under "Electrical Generators," paragraph 10 (a) (3).
- (b) Connect the generators in parallel, as shown in Fig. 60, and take simultaneous readings of load amperes; field amperes (shunt); armature amperes; equalizer amperes; bus bar volts.

4. Curves:

- (a) Plot on the same sheet the data obtained in run (a) using load current as abscissae, and field amperes and also terminal volts as ordinates.
- (b) Plot on the same sheet all data obtained in run (b), using load amperes as abscissae and all other amperes as ordinates; also bus bar volts as ordinates.

5. Answer in report:

- (a) In case the voltage of a shunt or compound generator will not build up, where would you look for the trouble and what would you do to correct it?
- (b) What are the advantages of parallel operation?
- (c) How would you disconnect a machine from a system, when operating in parallel with other generators?
- (d) Should a fuse be used in the equalizer circuit? Explain.

- (e) Explain briefly the action of the equalizer.
- (f) What is the effect of resistance in the equalizer circuit?

Experiment 17 — STARTING BOXES; NO-LOAD CHARACTERISTICS OF SHUNT MOTOR

- 1. Purpose.** To study construction and use of shunt motor starting boxes and also to determine no-load characteristics of shunt motor.
- 2. Apparatus.** Starting boxes; shunt motor; field ammeter; voltmeter; speed counter; stop watch; field rheostat; laboratory resistances; source of power.
- 3. Procedure:**
 - (a) Connect up laboratory resistances so as to start the motor in three separate steps. Choose resistances such that full load current is never exceeded.
 - (b) Connect a three-terminal starting box to motor.
 - (c) Connect a four-terminal starting box to motor.
 - (d) Connect a resistance in series with the armature and the line, for varying armature voltage. Connect ammeter in series with the field. Determine field excitation which will give rated speed at no-load, and keep this value constant during test. Gradually reduce armature voltage, taking readings of voltage and of speed.
 - (e) With connections as in (d), keep armature voltage constant and vary field excitation, never allowing motor to exceed 1.5 times rated speed, taking readings of field amperes and of speed.
- 4. Curves:**

- (a) Plot armature voltage as abscissae; speed as ordinates. (Data from (a).)
- (b) Plot field amperes as abscissae; speed as ordinates. (Data from (b).)

5. Answer in report:

- (a) Why is a starting box or rheostat necessary?
- (b) What is the necessity of a no-voltage release on a starting box?
- (c) What is the necessity of an overload release on a starting box?
- (d) What will happen if the field circuit of a shunt motor is broken while operating without load? With load?
- (e) Is the shunt field connected directly across the armature in starting a shunt motor? Explain.
- (f) Name three methods of controlling the speed of a shunt motor.

Experiment 18 — SHUNT MOTOR BRAKE TEST

- 1. Purpose.** To determine action of a shunt motor under varying load, using a Prony brake.
- 2. Apparatus.** Shunt motor; starting box; Prony brake; voltmeter; armature ammeter; field ammeter; speed counter; stop watch; field rheostat; source of power.
- 3. Procedure.** Connect motor to the line, using starting box. Connect field ammeter in series with the shunt field, and other ammeter in series with the armature and the line. Connect voltmeter across armature terminals.
 - (a) Determine brake zero (see Instructor).

- (b) Load motor to rated output for 15 minutes to heat it to operating conditions. Measure speed at full load and then remove load and again determine speed.
 - (c) With line voltage constant, and with field current kept at that value which gave rated speed at no load, start readings at no load and gradually increase load to one and one-fourth full load, reading motor input and output at regular intervals.
 - (d) Measure armature resistance (with motor at standstill), by voltmeter-ammeter method.
4. **Curves.** Plot output in horse power as abscissae; following as ordinates on same sheet:

Voltage	Efficiency
Field current	Torque
Amperes input	Speed
Power input	

5. **Answer in report:**

- (a) From data obtained in run (a), calculate the speed regulation of the motor.
- (b) What is the effect of armature reaction on the speed regulation of a shunt motor?
- (c) Discuss the speed characteristic of the shunt motor.
- (d) Discuss the torque characteristic of the shunt motor.
- (e) Where are shunt motors used?
- (f) How is it possible to reverse the direction of rotation of the shunt motor?

Experiment 19 — BRAKE TEST OF SERIES MOTOR

1. **Purpose.** To study speed characteristics of series motor, using Prony brake as load.
2. **Apparatus.** Series motor; starting box; regulating rheostat; ammeter; voltmeter; Prony brake; speed counter; stop watch; source of power.
3. **Procedure:**
 - (a) Connect motor in series with starting box, ammeter, regulating rheostat and source of power. Connect voltmeter across terminals of motor (so that it records drop across both field and armature). Keep voltage constant throughout test. Begin with motor 25 per cent overloaded, gradually reducing load in about equal steps, until safe maximum speed of motor is reached. At each step read volts, amperes, speed, and scale of Prony brake.
 - (b) Take a few readings with field shunted to weaken it slightly.
 - (c) Take a few readings with supply voltage about 10 per cent above and also a few with voltage 10 per cent below name-plate voltage.
4. **Curves:**
 - (a) Plot, from data taken in run (a), amperes input as abscissae; following as ordinates:

Speed	Efficiency
Torque	Horse power output
 - (b) Plot on same sheet, and to amperes input as abscissae, the results obtained from runs (b) and (c).
5. **Answer in report:**

- (a) Compare speed regulation of series motor with that of shunt motor.
- (b) What will happen to the series motor if the load is suddenly removed?
- (c) Describe precautions necessary in above test.
- (d) What uses are series motors especially adapted for and why?

Experiment 20 — COMPOUND MOTOR

1. **Purpose.** To compare speed characteristics of cumulatively compounded, differentially compounded, and shunt motors.
2. **Apparatus.** Compound motor; field ammeter; ammeter for armature circuit; voltmeter; Prony brake; speed counter; stop watch; regulating rheostat; source of power.
3. **Procedure:**
 - (a) Connect up machine as a shunt motor, and make a load run, reducing load in about equal steps from one and one-fourth load to zero load. Keep voltage on motor as constant as possible by means of rheostat in armature circuit. Adjust field so that rated speed is obtained at no load, and keep field current constant throughout tests at this value. Take readings of volts, amperes input, speed, and load.
 - (b) Repeat with motor cumulatively compounded. Start at same no load speed, loading motor to one and one-fourth load and then take readings reducing load as before.

- (c) Repeat with motor differentially compounded. Start at same no-load speed and take readings as in (a) and (b).

4. Curves. Plot three curves from data obtained in runs (a), (b), and (c), on same axes: Motor load as abscissae; speed as ordinates.

5. Answer in report:

- (a) What advantages have differentially compounded motors? What uses are they adapted for?
- (b) How does speed vary with load in differentially compounded motor?
- (c) What disadvantage does the differential motor have?
- (d) What advantages have cumulatively compounded motors? Where are they used?
- (e) How does the speed of the cumulatively compounded motor vary with the load?
- (f) What is meant by "speed regulation" of motor?
- (g) What is meant by "speed control" of motor?
- (h) How is it possible to tell whether motor is cumulatively or differentially connected?

INDEX

- Abscissa..... 25
 Absolute Reluctivity..... 74
 Accumulator (See Storage Cells), 155
 Acid Solution..... 141
 Action of Commutator..... 178
 Action of Commutator in Motor, 235
 Action of Interpole..... 211
 Active Material in Storage Cells..... 157
 Advantages of Three-wire System over Two-wire System.... 214
 Air Core..... 23
 Air Gap..... 168, 178
 Air Spaces..... 170
 Allowable Temperature Rise.... 50
 Alternating Current..... 6
 Aluminum..... 46
 Amalgamation..... 144
 American Wire Gauge..... 48
 Ammeters..... 87
 — Care and Precautions..... 98
 — Method of Connection..... 98
 Ammeters, Calibration (Experiment 1)..... 276
 Ammeter Shunt..... 88
 Ammonium Chloride..... 149
 Ampere..... 4, 7
 Ampere-hour Meters..... 111
 — Connection in Circuit..... 112
 — Description..... 111
 — Use..... 111
 Ampere-Turns..... 10
 Analogy between Mechanical Properties and Properties of the Electrical Circuit..... 43
 Anode..... 141
 Armature Core..... 168, 173
 — Drum Type..... 173
 — Slotted Type..... 173
 — Smooth Core Type..... 173
 Armature Current in Motor Limited by Counter E.M.F. 241
 Armature Reaction..... 201, 208
 — Definition..... 201
 — Effects Shown by Flux Diagrams..... 206
 — Illustration of Action by Vectors..... 202
 — Method of Reducing..... 206
 Armature Reaction in Motor... 250
 Armature Windings..... 168, 174
 Arrangement of Cells for Highest Efficiency..... 155
 Arrangement of Cells for Maximum Current..... 155
 "Ayrton" Shunt..... 128
 Balancing Instruments..... 98
 Banding Wires..... 175
 Bar-to-Bar Test..... 224
 Bare Conductors..... 50
 Batteries..... 152
 Battery..... 142
 Battery Jars..... 151
 Bearing Friction..... 198
 Bearing Pedestal..... 172
 Bearings..... 172
 Bed-Plate..... 172
 Bichromate Cell..... 148
 Binding Wires..... 175
 Bi-Polar Generators..... 169
 "Black" Commutation..... 208
 "Blondel" Method of Determining Efficiency..... 201
 Blue Vitriol..... 150
 Booster..... 201
 Brake Test of Series Motor (Experiment 19)..... 303

- Brake Test, Shunt Motor (Experiment 18)..... 301
 Brass Wedges..... 175
 Brass Wire..... 175
 British Thermal Unit..... 19
 Broken Connection..... 222
 Brown and Sharpe Wire Gauge..... 48
 Brush Bus..... 172
 Brush Friction..... 198
 Brush-Holder..... 171
 Brush Rigging..... 172
 Brush Shifting..... 172
 Brush Studs..... 172
 Brush Yoke..... 172
 Brushes..... 168, 170
 Brushes on Railway Motors..... 171
 Buckling..... 157
 Built-up Segments..... 174

 C. G. S. System..... 6
 Cables..... 36
 Calculation of Approximate Resistance of Copper Wire..... 48
 Calibration of Ammeters (Experiment 1)..... 276
 Calibration of Voltmeters (Experiment 2)..... 277
 Calibration of Watt-hour Meter..... 137, 138
 Capacitance..... 41
 Capacity..... 8, 41
 Capacity of Generators..... 213
 — Commutation..... 213
 — Excessive Voltage Drop..... 214
 — Size of Armature Windings..... 213
 — Ventilation..... 213
 Capacity of Storage Cells..... 161
 Carbon..... 148
 Cathode..... 141
 Cell..... 142
 Characteristics of Generators..... 185
 — Cumulatively Compounded .. 194
 — Differentially Compounded... 192
 — Series..... 190
 — Separately Excited..... 185
 — Shunt..... 187
 Charging Cells..... 158
 Chemical Depolarizers..... 143
 Chemical Effect..... 4
 Chemical Energy..... 141
 Circuit Breakers..... 56, 217
 Circuit Calculations..... 61
 Circuit Connections..... 56
 Circular-Mil..... 47
 Circular Mil-foot..... 47
 Clamping Bolts..... 178
 Clamping Rings..... 178
 Classes of Cells..... 147
 — Closed Circuit Cells..... 147
 — Open-Circuit Cells..... 147
 Classification of Motors..... 252
 — Compound..... 253
 — Cumulative..... 254
 — Differential..... 254
 — Series..... 253
 — Shunt..... 252
 Closed Circuit..... 56
 Closed-circuit Cells..... 147
 — Bichromate..... 148
 — Crowfoot..... 148, 150
 — Edison Lalande..... 148
 — Fuller..... 148
 — Gravity..... 148
 Closed-circuit E.M.F. of Cells... 145
 Coil, Ruhmkorff..... 45
 Commercial Efficiency..... 190
 Commutation..... 208
 — Resistance..... 212
 Commutator..... 168, 175, 177
 Commutator Action..... 178
 Commutator Bars..... 175
 Commutator Lugs..... 175
 Commutator Type Watt-hour Meter..... 103
 Comparison of Voltmeter De-

lections Using Standard Resistance.....	124	Convection.....	53
— Method of Connection.....	124	Copper.....	46
— Theory.....	124	Copper Bars, Hard-drawn.....	177
— Where Used.....	124	Copper Gauze Brushes.....	171
Compensating Coil.....	101, 207	Copper Leaf Brushes.....	171
Compound Generator.....	192	Copper Losses.....	198
— Cumulative.....	192	— In Armature Winding.....	199
— Differentially Compounded...	194	— In Field Winding.....	199
— Flat Compounded.....	193	— In Other Windings.....	199
— Long Shunt.....	184	Copper Sulphate.....	150
— Over Compounded.....	194	Copper Sulphate Solution.....	150
— Short Shunt.....	184	Copper Wire.....	36
— Under Compounded.....	194	Core Losses (See Iron Losses)...	
Compound Generator Operation,	219	Corona.....	4
— Action of Equalizer.....	219	Cotton Insulation.....	36
— Requirements for Parallel		Coulomb.....	8
Operation.....	219	Counter E.M.F.....	235
— Starting.....	219	Counter E.M.F. in Motor Lim-	
— Stopping.....	219	ited by Speed.....	241
— Throwing in Parallel.....	220	Counter-Torque.....	239, 241
Compound Generators, Load		Critical Resistance.....	191
Characteristics (Experiment		Crowfoot Cell.....	150
14).....	295	Cumulative Motor.....	254
Compound Generators in Paral-		Cumulatively Compounded Gen-	
lel (Experiment 16).....	298	erator.....	192
Compound Motor.....	253, 304	Cuprous Oxide.....	143
Compound Motor Operation....	271	Current.....	4
Compressed Powdered Coke....	170	Current-Carrying Capacity.....	50
Condenser.....	42	Current Flow.....	7
Conditions for Sparkless Commu-		Current Leakage.....	36
tation.....	208	Current Measurement.....	115
Conditions for Sparkless Commu-		— With Ammeter.....	115
tation in Motor.....	251	— With Standard Resistance and	
Conductance.....	5	Voltmeter.....	115
Conduction.....	52	Currents at an Angle.....	29
Conductors.....	36	Damping.....	95
Conservation of Energy.....	18	Damp-proof Varnish.....	175
Constant of Galvanometer.....	130	D'Arsonval Galvanometer.....	88
Constant of Watt-hour Meter...	106	Dead-beat Instruments.....	89, 94
Construction of Generator.....	168	Definition of Energy.....	18
Construction of Motor.....	235	Definition of Power.....	15
Continuous Current.....	6	Degree, Electrical.....	175

- Depolarizers..... 143 — Apparatus Required..... 128
 — Chemical..... 143 — Method of Connection..... 128
 — Electrochemical..... 143 — Operation..... 130
 — Mechanical..... 144 — Theory..... 130
 Description of Cells..... 148 — Where Used..... 128
 — Dry..... 149 Direction of Induced Current... 167
 — Gravity or Crowfoot..... 150 Discharging Cells..... 158
 — Leclanche..... 148 Discussion of Magnetic Curves.. 26
 Design Factors in Motor Distinction between Dynamo
 Speed..... 242 and Generator..... 167
 Determination of Internal Re- Distortion..... 203
 sistance of Cells..... 145 Divided Circuits..... 21
 Determination of Motor Effi- Drum-Type Armature Core.... 173
 ciency..... 249 Dry Cell..... 147, 149, 150
 — Directly..... 249 Dynamo..... 167
 — Indirectly..... 250 D y n a m o m e t e r-Type Instru-
 — Opposition Methods..... 250 ments..... 96
 Determination of Working Re- Dynamometer-Type Wattmeters, 99
 sistance of Cells..... 146 — Compensation..... 101
 Determining Efficiency of Gen- — Corrected for Power Con-
 erator..... 199 sumed in Instrument Itself... 100
 — Directly..... 199 — Description..... 99
 — Indirectly..... 200 — Method of Calibration..... 100
 Difference of Potential..... 5 — Method of Connection..... 100
 Differential Motor..... 254 E.M.F. of Cells..... 144
 Differently Compounded Genera- — Closed Circuit..... 145
 tor..... 194 — Open Circuit..... 144
 Direct Current..... 6 Ebonite..... 36
 Direct Current Generators..... 167 Eccentric Pole Shoes..... 207
 — Commutator and Brushes.... 168 Eddy Currents..... 77
 — Electrical Circuits..... 168 Eddy-Current Brake..... 104
 — Magnetic Circuit..... 168 Eddy-Current Losses..... 196
 Direct-Current Measurements... 115 Edison Cell..... 159
 — Current..... 115 Edison Lalande Cell..... 148
 — Energy..... 137 Effects of Armature Reaction
 — Power..... 135 Shown by Flux Diagram..... 206
 — Resistance..... 117 Effects of Brush Shifting.... 204, 205
 — Voltage..... 115 Effects of Changing Magnetism.. 76
 Direct-Current Motor..... 232 Effects of Hysteresis..... 25
 Direct Deflection Method (Ex- Effect of Temperature Expressed
 periment 10)..... 289 as an Equation..... 49
 Direct Deflection Method for In- — Numerical Example..... 50
 sulation Resistance..... 128

Effects of Temperature on Resistance.....	49	Electricity, Elementary Terms...	4
Efficiency of Generator.....	199	Electrochemical Action	6
— Blondel Method.....	201	Electrochemical Depolarizers....	143
— How Determined.....	199	Electrodes.....	141
— "Opposition" Methods.....	201	Electrolysis.....	4
— "Pumping Back" Methods...	201	Electrolyte.....	141
Efficiency of Motor.....	249	Electromagnetic Laws.....	27
— Definition.....	249	— Currents at an Angle.....	29
— How Determined.....	249	— Field about a Helix.....	28
Electrical Causes of Sparking...	208	— Field about a Straight Con-	
— Armature Reaction.....	208	ductor.....	27
— Self-Induction.....	210	— Law of Generator Action....	30
Electrical Circuits.....	36	— Laws of Magnetic Action	
Electrical Circuits of Generator..	168	between Current-Carrying	
Electrical Degree.....	175	Conductors.....	28
Electrical Generator.....	167	— Lenz's Law.....	32
Electrical Heating.....	20	— Maxwell's Law of Motor	
Electrical Input (Motor).....	248	Action.....	29
Electrical Instruments.....	87	— Parallel Currents in Opposite	
— Ammeters.....	87	Directions.....	29
— Ampere-hour Meters.....	111	— Parallel Currents in the Same	
— Dead-beat.....	89, 94	Direction.....	28
— Voltmeters.....	87	— Production of Magnetic Field	
— Watt-hour Meters.....	102	by Electric Current.....	27
— Wattmeters.....	99	Electromagnetic System.....	7
Electrical Load.....	104	Electromagnetism.....	10
Electrical Power.....	15	Electromotive Force.....	4, 7
Electrical Power Stated as an		Electrons.....	3
Equation.....	16	Electro-plating.....	4, 171
Electrical Power in Terms of		Electrostatic System.....	7
Resistance.....	16	Electrostatic Voltmeters.....	97
Electrical Pressure.....	7	Elementary Electrical Terms....	4
Electrical Unit of Heat.....	20	— Alternating Currents.....	6
Electrical Units.....	6	— Conductances.....	5
Electricity.....	3	— Current.....	4
— Chemical Effect.....	4	— Direct Current.....	6
— Heating Effect.....	3	— Electromotive Force.....	4
— How Manifested.....	3	— Inductance.....	5
— How Measured.....	4	— Potential.....	5
— Magnetic Effect.....	3	— Resistance.....	5
— Physiological Effect.....	4	Elementary Magnetic Terms....	9
— Visible Effect.....	4	— Lines of Force.....	9
		— Magnetic Field.....	9

- Magnetic Flux..... 9
- Magnetomotive Force..... 10
- Permeance..... 10
- Polarity..... 10
- Reluctance..... 10
- End Bells..... 172
- End Frames..... 172
- Energy Measurement..... 137
- Energy of Motion..... 18
- Equalizer..... 219
- Equations of Electrical Energy.. 18
- Numerical Example..... 19
- Essentials of all Direct Current
 - Generators..... 168
 - Air Gap..... 168
 - Armature Core..... 168
 - Armature Windings..... 168
 - Field Frame..... 168
 - Field Windings..... 168
 - Pole Pieces..... 168
 - Pole Shoes..... 168
- Essentials of Direct-Current
 - Motors..... 235
- Excessive Heating..... 223
- Armature..... 223
- Bearings..... 224
- Commutators and Brushes... 223
- Field Windings..... 223
- Excessive Sparking..... 222
- Electrical Causes..... 222
- Mechanical Causes..... 223
- Excessive Speed of Motors..... 272
- Excitation of Generators..... 181
- Self-Excitation..... 182
- Separate Excitation..... 181
- Factors Determining Heat Dis-
 - sipated..... 52
- Factors Determining Heat Gen-
 - erated..... 51
- Factors Determining Internal
 - Resistance of Cells..... 145
- Factors Determining Magnetic
 - Force Exerted in Motor..... 237
 - Armature Current..... 237
 - Field Strength..... 237
 - Length of Conductor..... 238
- Factors Determining Motor
 - Speed..... 241
- Factors Determining Tempera-
 - ture Rise..... 50
 - Failure to Build Up..... 221
 - Failure to Carry Load..... 222
 - Failure to start, Motors..... 272
 - Farad..... 8
 - Faraday's Law..... 30
 - Faure Cells..... 158
 - Ferro-Magnetic Materials..... 70
 - Ferro-Magnetic Substances.... 23
 - Chromium..... 23
 - Cobalt..... 23
 - Iron..... 23
 - Magnetite..... 23
 - Manganese..... 23
 - Nickel..... 23
 - Fiber..... 175
 - Fiber Wedges..... 175
 - Field about a Helix..... 28
 - Field About a Straight Con-
 - ductor..... 27
 - Field Frame..... 168
 - Field Intensity..... 11
 - Field Windings..... 168, 170
 - Flame-Proof Motor..... 235
 - Flat Compound Generator.... 193
 - Flexible Cable..... 172
 - Flint Glass..... 36
 - Flux Density..... 11, 25
 - Flux Shifting in Generator..... 203
 - Foot-Pound..... 17
 - Forged Steel Shaft..... 178
 - Formed Cells..... 158
 - Foucault Currents..... 77, 196
 - Friction Compensation..... 110
 - Friction Losses..... 198
 - Bearing Friction..... 198

- Brush Friction..... 198
- Windage..... 198
- Fuller Cell..... 148
- Fundamental Laws of Electrical Engineering..... 14
- Kirchhoff's Law..... 21
- Laws of Electrical Energy and Electrical Heating..... 18
- Laws of Electrical Power..... 15
- Ohm's Law..... 14
- Fundamental Principle of Generator..... 167
- Fundamental Principle of Motor, 232
- Fuses..... 56, 217
- Galvanometer..... 88
- Galvanometer Constant..... 130
- Generator Action in Motor.. 233, 234
- Generator Capacity..... 213
- Generator Characteristics (See Characteristics of Generators) 185
- Generator Excitation..... 181
- Generator Efficiency..... 199
- Generator as Motor..... 233
- Generator Construction..... 168
- Generator Operation..... 216
- Generator Regulation..... 196
- Losses..... 196
- Generator Tests..... 224
- Ground..... 226
- Open-Circuit..... 226
- Short-Circuit..... 224
- Generators..... 6, 167
- Cast-Iron Frame..... 168
- Cast-Steel Frame..... 168
- Compounded..... 192
- Cumulative..... 192
- Differential..... 194
- Flat..... 193
- Interpole..... 211
- Pedestal..... 172
- Rotating Parts..... 173
- Self Excited..... 182
- Separately Excited..... 185
- Series..... 190
- Shunt..... 187
- Three-Wire..... 214
- Generators, Troubles..... 221
- German Silver Grids..... 193
- Graphite..... 170
- Gravity Cell..... 150
- Grids..... 157, 160
- Ground in Field Winding..... 221
- Ground Tests..... 226
- Armature Winding..... 226
- Field Winding..... 226
- Guard Wire..... 128, 129
- Gutta Percha..... 36
- Handwheel for Brush Shifting... 172
- Heat Energy..... 19
- Heat Transfer..... 52
- Heating Coil..... 110
- Heating Effect..... 3
- Heating of Motors..... 272
- Henry..... 5, 8
- Heusler Alloys..... 69
- Homopolar Motor..... 106
- Horse Power..... 17, 247
- Hot-Wire Type Instruments.... 97
- "Hutchinson" Test..... 201
- Hydrogen..... 143
- Hysteresis..... 25, 76
- Hysteresis Loss..... 76, 197
- Impregnated Coils..... 174
- Incorrect Brush Location..... 222
- Independent Terminal of Wattmeter..... 102
- Indicating Wattmeters..... 99
- Indicator Cards..... 199
- Induced E.M.F..... 5
- Inductance..... 5, 8, 37
- Induction Instruments..... 97
- Insulated Compound..... 174
- Insulated Linen Tape..... 174

- Insulation Resistance — Direct Deflection Method (Experiment 10)..... 289
- Insulation Resistance, Voltmeter Method (Experiment 9)..... 289
- Insulation Test by Substitution.. 128
- Insulators..... 36
- Internal Resistance of Cells..... 145
- Constant Factors..... 145
- Determination of Internal Resistance..... 146
- Determination of Total Resistance..... 146
- Variable Factors..... 146
- Interpole Windings..... 170
- Interpole..... 211
- Actions..... 211
- Definition..... 211
- How Connected..... 211
- Interpoles (In Motors)..... 251
- Iron-Bar Type Instruments..... 95
- Iron Grids..... 193
- Iron Losses..... 196
- Eddy Current..... 196
- Hysteresis..... 197
- Iron Vane Instruments..... 93
- Joule..... 8, 20
- Kelvin Double Bridge..... 121
- Kilowatt-hour..... 8, 19
- Kinetic Energy..... 18
- Kirchhoff's Laws..... 21
- Application to More Complex Circuits..... 22
- Divided Circuits..... 21
- How Derived..... 21
- Numerical Illustration of First Law..... 21
- Numerical Illustration of Second Law..... 21
- Statement of Kirchhoff's First Law..... 21
- Statement of Kirchhoff's Second Law..... 21
- Kirchhoff's First Law..... 21
- Kirchhoff's Second Law..... 21
- Laminated Core..... 173
- Laminations..... 78, 169
- Lap Winding..... 175
- Lap-Wound Motor..... 243
- Laws of Electrical Energy and Electrical Heating..... 18
- Law of Electromagnetic Induction..... 30
- Law of Generator Action..... 30
- Laws of Electrical Power..... 15
- Laws of Magnetic Action between Current-Carrying Conductors..... 28
- Laws of Magnetic Circuit with Iron or Other Ferro-Magnetic Substance..... 24
- Lead Cells..... 157
- Faure..... 158
- Formed..... 158
- Pasted..... 158
- Plante..... 158
- Lead Peroxide..... 157
- Lead Sulphate..... 157
- Leakage Flux..... 71
- Leclanche Cell..... 147, 148
- Lenz's Law..... 32
- Lenz's Law Applied to the Generator..... 167
- Limitation of Output, Motors... 273
- Lines of Force..... 9
- Lithium Hydrate..... 159
- Load Characteristics of Compound Generators (Experiment 14)..... 295
- Load Characteristics of Shunt Generator (Experiment 12).... 291
- Local Action..... 144
- Lode-stone..... 10
- Loss of Residual Magnetism.... 221

Losses in Generator.....	196	— Numerical Example.....	24
— Bearing Friction.....	198	Magnetic Materials.....	69
— Brush Friction.....	198	Magnetic Resistance.....	10
— Copper.....	198	Magnetic Units — Practical Sys-	
— Core.....	196	tem.....	11
— Eddy Current.....	196	— Ampere-turn.....	11
— Friction.....	198	— Field Intensity.....	11
— Hysteresis.....	197	— Flux Density.....	11
— Iron.....	196	— Maxwell.....	11
— Mechanical.....	196	— Rel.....	11
— Stray Power.....	196	Magnetism.....	9
— Windage.....	198	— Definition.....	9
Losses in Motor.....	249	— Elementary Terms.....	9
— Copper.....	249	— How Measured.....	9
— Stray Power.....	249	— How Obtained.....	9
Low Resistance in Conductors... 36		Magnetization Curves.... 25, 26, 186	
Lugs, Commutator.....	175	Magnetomotive Force..... 10, 11	
Magnet Cores.....	169	Magnitude of Induced E.M.F.... 30	
Magnetic Action.....	232	Manganese Dioxide..... 143, 148	
Magnetic Circuits..... 9, 69		Manganin.....	92
Magnetic Circuit Calculations... 81		Materials, Ferro-Magnetic..... 70	
— Numerical Example.....	81	Materials, Magnetic.....	69
Magnetic Circuit Connections... 79		Materials, Non-Magnetic..... 70	
— Parallel.....	79	Materials Used in Electrical Cir-	
— Series.....	79	cuits.....	36
— Series-Parallel.....	79	Maxwell.....	11
Magnetic Circuit of Four-Pole		Maxwell's Laws.....	29
Dynamo.....	80	Maxwell's Law of Motor Action. 29	
Magnetic Circuit of Generator... 168		Measurement of Comparatively	
Magnetic Drag..... 77, 104		Low Resistance by Voltmeter-	
Magnetic Effect.....	3	Ammeter Method.....	123
Magnetic Field.....	9	Measurement of Current..... 115	
Magnetic Flux..... 9, 11		— With Ammeter.....	115
Magnetic Intensity.....	25	— With Standard Resistance	
Magnetic Laws.....	23	and Voltmeter.....	115
— Laws of Magnetic Circuit with		Measurement of High Resistance	
Iron or Other Ferro-Magnetic		by Voltmeter-Ammeter Method 123	
Substance.....	23	Measurement of Power..... 135	
— Ohm's Law for the Magnetic		Measurement of Resistance..... 117	
Circuit.....	23	— Comparisons of Voltmeter	
Magnetic Law Stated as an		Deflections.....	124
Equation.....	23	— Direct Deflection Method for	
		Insulation Resistance.....	128

- Kelvin Double Bridge..... 121
- Slide-wire Bridge..... 120
- Voltmeter-Ammeter Method.. 122
- Voltmeter Method for Insulation Resistance..... 125
- Wheatstone Bridge..... 117
- Measurement of Resistance, by Comparison of Voltmeter Deflections, Using Standard Resistance (Experiment 8)..... 287
- Measurement of Resistance Using Wheatstone Bridge (Experiment 6)..... 284
- Measurement of Voltage..... 115
- With Voltmeter — Above its Range..... 116
- With Voltmeter — Below its Range..... 116
- With Voltmeter — Within its Range..... 115
- Measuring Instruments Used with Generators..... 216
- Measuring Insulation Resistance of Insulated Wires..... 128
- Measuring Resistance, Voltmeter-Ammeter Method (Experiment 7)..... 286
- Mechanical Analogy of Ohm's Law 14
- Mechanical Depolarizers..... 144
- Mechanical Losses (See Friction Losses).....
- Mechanical Power..... 17
- Megohm..... 37
- Method of Connecting Voltmeters and Ammeters..... 98
- Method of Determining Amount of Electrical Energy..... 18
- Method of Reducing Armature Resistance..... 206
- Compensating Coil..... 206
- Eccentric Pole Shoes..... 207
- Introduction of Reluctance in Path of Flux..... 207
- Saturated Pole Tips..... 207
- Mica..... 175
- Micro-farad..... 8, 42
- Mil..... 47
- Mil-Foot..... 47
- Milli-henry..... 8, 37
- Millivoltmeter..... 115
- Mirror-type Galvanometer..... 128
- Moisture-Proof Motor..... 235
- Molded Mica Segments..... 177
- Motor..... 232
- Efficiency..... 249
- Input..... 248
- Losses..... 249
- Output..... 247
- Motor Action..... 232
- Motor Action of Commutator... 235
- Motor Applications..... 261
- Cumulative..... 262
- Differential..... 262
- Series..... 261
- Shunt..... 261
- Motor Characteristics..... 254
- Cumulatively Compounded Motor..... 254
- Differentially Compounded Motor..... 254
- Series Motor..... 253
- Shunt Motor..... 254
- Motor Construction..... 235
- Motor Protective Devices..... 272
- Circuit-Breakers..... 272
- Fuses..... 272
- Motor Rating..... 273
- Motor Speed Control..... 245
- Applied E.M.F..... 245
- Field Strength..... 245
- Motor Speed..... 241
- Motor Speed Regulation..... 246
- Definition..... 246
- Numerical Example..... 246
- Speed Regulation Expressed as Equation..... 246

Motor Tests.....	273	No-Field Release.....	264
Motor Torque.....	238	No-load and Load Tests of	
— Definition.....	238	Series Generator (Experiment	
— Determined by Counter-		13).....	293
Torque.....	239	No-Load Neutral Plane....	202, 204
— Numerical Example.....	241	No-Load Test of Shunt Genera-	
— Torque and Power.....	240	tor (Experiment 11).....	290
— Torque Expressed as an Equa-		Non-Conductors.....	36
tion.....	240	Non-Magnetic Materials.....	70
— Torque Independent of Speed	240	Northern Lights.....	4
— Unit of Measurement.....	238	No-Voltage Release.....	268
Motor Troubles.....	272	North Pole.....	10
— Excessive Speed.....	272	No. 10 Copper Wire.....	48
— Failure to Start.....	272	Numerical Application of Kirch-	
— Heating.....	272	hoff's Laws.....	67
— Sparking.....	272	Numerical Example of Electrical	
— Under-speed.....	272	Heating.....	20
Motor, Use of Multi-Coils.....	236	Numerical Example of Electri-	
Moving Coil and Stationary Coil		cal Power.....	16
Type Instruments.....	96	Numerical Examples of Ohm's	
Moving Coil and Stationary Perma-		Law.....	15
nent Magnet Type Instru-			
ments.....	88	Ohm.....	5, 7
Multi-Coils, Use of.....	180	Ohm's Law.....	14
Multi-Polar Generators.....	169	Ohm's Law for the Magnetic	
Multi-Voltages, Use of.....	267	Circuit.....	23, 73
Multiple Arrangement of Cells...	153	Ohm's Law Stated as an Equa-	
Multiple Winding.....	175	tion.....	14
Multiplier.....	87	Ohms per Inch Cube.....	46
		Ohms per Mil-foot.....	46
Name Plate.....	200	Oil Wells.....	178
Natural Magnet.....	10	Oiling Rings.....	178
Negative Pole.....	142	Open Circuit.....	56
Network.....	60	Open Circuit Calculations.....	61
Network Calculations.....	65	Open Circuit in Field or Arma-	
Neutral Plane.....	202, 204	ture.....	221
New Neutral Plane.....	206	Open-circuit Cells.....	147
Nickel.....	159	— Dry Cell.....	147
Nickel-Iron-Alkaline Cell.....	159	— Leclanche' Cell.....	147
Nickel Hydrate.....	159	Open-circuit E.M.F. of Cells....	144
Nitric Acid.....	143	Open-Circuit Tests.....	226
No-Commutator Type Watt-		— Armature Winding.....	226
hour Meter.....	106	— Field Winding.....	227

- Open Motor..... 235
 Operating of Generators..... 216
 — Compound..... 219
 — Measuring Instruments Necessary..... 216
 — Protective Devices..... 217
 — Shunt..... 217
 Operation..... 262, 270, 271
 — Compound Motors..... 271
 — Series Motors..... 270
 — Shunt Motors..... 262
 Operation of Shunt Generators
 In parallel (Experiment 15)..... 296
 "Opposition" Tests..... 201
 Ordinate..... 25
 Over-compounded Generators... 194
 Overload Release..... 265
 Oxygen..... 157

 Paper Insulated Cables..... 50
 Paraffin..... 36, 151
 Parallel Arrangement of Cells... 153
 Parallel Circuit..... 58
 Parallel Circuit Calculations... 62
 Parallel Connection..... 52
 Parallel Currents in Opposite
 Directions..... 29
 Parallel Currents in Same Direc-
 tion..... 28
 Parallel Magnetic Circuit..... 79
 Parallel Operation..... 218, 219, 220
 — Compound Generators... 219, 220
 — Shunt Generators..... 218
 Parallel Operation of Compound
 Generators (Experiment 16)... 298
 Parallel Operation of Shunt
 Generators (Experiment 15)... 296
 Parallel Winding..... 175
 Pasted Cells..... 158
 Percentage Voltage Regulation
 of Generator..... 196
 Permanent Magnet..... 11
 Permeability..... 72
 Permeance..... 10
 Permittance..... 41
 Phosphor Bronze Wire..... 175
 Physiological Effect..... 4
 Pig-Tail..... 171
 Plante' Cells..... 158
 Plates..... 141
 Platinum..... 46
 Plunger Type Instruments..... 94
 Polarity..... 10
 Polarization..... 143
 — Chemical Depolarizers..... 143
 — Electrochemical Depolarizers. 143
 — Explanation of Action..... 143
 — Mechanical Depolarizers.... 143
 — Prevention..... 143
 Pole Pieces..... 168, 169
 Pole Shoes..... 168, 169
 Poles..... 10, 141
 Portable Instruments..... 91
 Positive Pole..... 142
 Potassium Bichromate..... 143
 Potassium Hydrate..... 159
 Potential..... 5
 Potential Energy..... 18
 Potentiometer..... 145
 Pounds-Feet..... 241
 Powdered Carbon..... 149
 Powered Iron Oxide..... 160
 Power Input (Motor)..... 248
 — Determining Factors..... 248
 — Electrical Input Expressed as
 Equation..... 248
 — Numerical Example..... 248
 Power Measurement..... 135
 — With Ammeter and Volt-
 meter..... 135
 — With Wattmeter..... 135
 — With Wattmeter and Am-
 meter and Voltmeter..... 135
 Power Output of Motor..... 247
 — Determining Factors..... 247
 — How measured..... 247

— Numerical Example.....	247	Radial Ducts.....	174
— Output expressed as Equation.....	247	Radiation.....	54
Practical System.....	6	Radiation from Rough Surfaces..	54
Prevention of Polarization.....	143	Radiation from Smooth Sur- faces.....	54
Primary Cells.....	6, 141	Rate of Discharge of Storage Cells	161
— Arrangement for Highest Efficiency.....	155	Rating of Motors.....	273
— Arrangement for Maximum Current.....	155	Registering Mechanism.....	110
— Batteries.....	152	— Ampere-hour Meters.....	112
— Classes of Cells.....	147	— Watt-hour Meters.....	110
— Closed Circuit Cells.....	145, 147	Regulation of Generator.....	196
— Crowfoot Cell.....	148	Rel.....	11
— Dry Cell.....	147	Relation between Coulombs, Voltage and Capacitance....	43
— E.M.F. of Cells.....	144	— Numerical Example.....	43
— Edison Lalande Cell.....	148	Relation between Electrical Power and Mechanical Power.	17
— Fuller Cell.....	148	— Numerical Example.....	17
— Gravity Cell.....	148	Relative Reluctivity.....	74
— Leclanche' Cell.....	147	Reluctance.....	10, 11, 24
— Local Action.....	144	Reluctance of Magnetic Mate- rials.....	71
— Open-Circuit Cells.....	145, 147	Reluctance of Non-Magnetic Materials.....	73
— Parallel Arrangement.....	153	Reluctivity.....	72
— Polarization.....	143	Reluctivity, Absolute.....	74
— Principle of Operation.....	142	Reluctivity, Relative.....	74
— Series Arrangement.....	152	Requirements for Constant Speed in Motor.....	241
— Series-Parallel Arrangement..	154	Residual Magnetism.....	182
Production of Magnetic Field by Electrical Current.....	27	Resistance.....	5, 37
Prony Brake.....	248	Resistance Commutation.....	212
Properties Determining Resist- ance.....	46	Resistivity.....	46
Properties of Electrical Cir- cuits.....	37	Reversed Field.....	221
— Capacity.....	41	Revolution, Motor.....	248
— Inductance.....	37	Right-hand Rule.....	27, 167
— Mechanical Analogy.....	43	Rubber.....	36
— Resistance.....	37	Rubber-Insulated Cables.....	50
Protected Motor.....	235	Rubber Insulating Compound...	36
Protective Devices.....	217	Ruhmkorff Coil.....	45
Protective Devices, Motors.....	272		
Pulsating Current.....	6	Safe Carrying Capacities.....	55
"Pumping Back" Tests.....	201	Sal Ammoniac.....	149

- Salt Solution..... 141
 Sangamo Watt-hour Meter..... 107
 Saturated Pole Tips..... 207
 Saturation..... 26, 71, 186
 Secondary Cells (See Storage Cells)..... 155
 Segments, Molded Mica..... 177
 Self-Excited Generators..... 182
 — Compound..... 184
 — Series..... 183
 — Shunt..... 183
 Self-Induction..... 210
 Separately Excited Generators..... 181, 185
 — Load Characteristic..... 186
 — Magnetization Curve..... 186
 — No-load Characteristic..... 185
 — Speed Characteristic..... 186
 Series Arrangement of Cells..... 152
 Series Circuit..... 56
 Series Circuit Calculations..... 62
 Series Coils..... 170
 Series Connection..... 52
 Series Field Reversed..... 222
 Series Generator..... 183, 190
 — Critical Resistance..... 191
 — External Characteristic Curve..... 191
 — Internal Characteristic Curve..... 191
 — Load Characteristic..... 191
 — Magnetization Curve..... 190
 Series Generator, No-load and Load Tests (Experiment 13)... 293
 Series Magnetic Circuit..... 79
 Series Motor..... 253
 Series Motor, Brake Test (Experiment 19)..... 303
 Series Motor Operation..... 270
 — Operating and Controlling... 271
 — Speed Variation..... 270
 — Starting..... 270
 Series-Parallel Arrangement of Cells..... 154
 Series-Parallel Circuit..... 59
 Series-Parallel Circuit Calculations..... 64
 Series-Parallel Magnetic Circuit..... 79
 Series Shunt..... 193
 Series Winding..... 176
 Shaft of Generator..... 178
 Shifting of Brushes to get Sparkless Commutation..... 210
 Short-Circuit..... 56
 Short-Circuited Coil..... 208
 Short-Circuit Tests..... 224
 — Armature Winding..... 224
 — Bar-to-Bar Test..... 224
 — Field Windings..... 227
 Shunt..... 88
 Shunt Coils..... 170
 Shunt Generator..... 183, 187
 — Load Characteristic..... 188
 — No-load Characteristic..... 187
 — Speed Characteristic..... 188
 Shunt Generator Operation..... 217
 — Shunt Generators in Parallel.. 218
 — Starting..... 217
 — Stopping..... 218
 Shunt Generators in Parallel... 218
 Shunt Generator, Load Characteristics (Experiment 12)... 291
 Shunt Motor..... 252
 Shunt Motor Brake Test (Experiment 18)..... 301
 Shunt Motor Operation..... 262
 — Operating and Controlling... 268
 — Speed Variation..... 266
 — Starting..... 262
 — Starting Box..... 263
 — Stopping..... 269
 Silk Insulation..... 36
 Silver Nitrate Solution..... 7
 Slide-wire Bridge..... 120
 Slotted Armature Core..... 173
 Slotted Pole Cores..... 207

Slotted Pole Shoes.....	207	— Capacity.....	161
Smooth Core Armature.....	173	— Charging.....	158
Solenoid.....	11, 28	— Definition.....	155
South Pole.....	10	— Discharging.....	158
Southern Lights.....	4	— Edison Cells.....	159
Spacing Pieces.....	174	— Faure.....	158
Sparkling of Motors.....	272	— Formed.....	158
Sparkless Commutation, 208, 210, 211		— Lead Cells.....	157
— By Shifting Brushes.....	210	— Nickel-Iron-Alkaline Cells....	159
— By Use of Interpoles.....	211	— Pasted.....	158
Sparkless Commutation in		— Plante'.....	158
Motor.....	251	— Principles of Operation.....	156
Specific Gravity of Storage		— Specific Gravity.....	158, 160
Cells.....	158, 160	— Uses.....	161, 162
Specific Resistance.....	46	Stranded Conductor.....	54
Speed Characteristic of Cumu-		Stray Power Losses.....	196
lative Compound Motor.....	260	— Bearing.....	198
Speed Characteristic of Differ-		— Brush.....	198
ential Compound Motor.....	260	— Core.....	196
Speed Characteristic of Series		— Eddy Current.....	196
Motor.....	257	— Friction.....	198
Speed Characteristic of Shunt		— Hysteresis.....	197
Motor.....	254	— Iron.....	196
Speed Control of Motors.....	245	— Mechanical.....	198
Speed Factors Expressed as		— Windage.....	198
Equation.....	244	Study of Direct-Current Am-	
— Numerical Example.....	244	meters and Voltmeters (Ex-	
Speed of Motors.....	241	periment 3).....	278
Speed Variations.....	266	Study of Watt-hour Meter (Ex-	
— Applied E.M.F.....	266	periment 5).....	281
— Field Strength.....	266	Study of Wattmeter (Experi-	
Spider.....	174	ment 4).....	279
Standard Resistance.....	115	Sulphating.....	157
Starting Boxes.....	268	Sulphuric Acid.....	150
Starting Boxes, No-load Char-		Switchboard Instruments.....	90
acteristics of Shunt Motor		Tachometer.....	248
(Experiment 17).....	300	Temperature Coefficient.....	49
Statement of Magnetic Law....	23	Temperature Rise, Allowable....	50
Static Electricity.....	42, 97	Terminal Board.....	172
Stationary Coil and Moving		Terminals.....	141
Iron Instruments.....	93	Thermo-couple.....	110
Stop Watch.....	245	Three-Wire Generator.....	214
Storage Cells.....	158		

- Advantages..... 216
- Allowable Unbalancing..... 216
- Principle of Operation..... 214
- Three-wire System Watt-hour
Meter..... 137
- Tinned Steel Wire..... 175
- Torque and Power..... 240
- Torque Characteristic of Cumulative Compound Motor..... 260
- Torque Characteristic of Differential Compound Motor.... 260
- Torque Characteristic of Series Motor..... 258
- Torque Characteristic of Shunt Motor..... 256
- Torque Determined by Counter-Torque..... 239
- Torque Developed by Means of Armature Current..... 241
- Torque Expressed as Equation.. 240
- Numerical Example..... 241
- Torque Independent of Speed... 240
- Tracing Starting Box Connections..... 265
- Troubles in Generators..... 221
- Excessive Heating..... 223
- Excessive Sparking..... 222
- Failure to Build Up..... 221
- Failure to Carry Load..... 222
- Two-Circuit Winding..... 176
- Types of Storage Cells..... 157
- Edison..... 159
- Faure..... 158
- Formed..... 158
- Lead..... 157
- Nickel-Iron-Alkaline..... 159
- Pasted..... 158
- Plante..... 158
- Typical Magnetic Circuit Problem..... 81
- Under-compounded Generator... 194
- Under-speed, Motors..... 272
- Unit of Energy..... 8
- Unit Quantity..... 8
- Unit Reluctance..... 72
- Unit Resistance of Various Materials..... 46
- Unit Used for Storage Cells.... 161
- Units — Practical System..... 8
- Capacity..... 8
- Current Flow..... 7
- Electromotive Force..... 7
- Energy..... 8
- Inductance..... 8
- Power..... 8
- Quantity..... 8
- Resistance..... 7
- Work..... 8
- “Universal” Shunt..... 128
- Use of Multi-Coils..... 180, 236
- Use of Multi-Voltages..... 267
- Use of Storage Batteries.... 161, 162
- Uses of Edison Cells..... 161
- Uses of Gravity Cell..... 152
- Value of Induced E.M.F. Expressed as an Equation..... 31
- Variation of Reluctance Expressed as an Equation..... 73, 75
- Numerical Examples..... 73, 75
- Variation of Reluctance with Dimensions..... 74
- Variation of Reluctance with Flux Density..... 71
- Variation of Reluctance with Material..... 71
- Variation of Resistance Expressed as Equation..... 47
- Numerical Example..... 48
- Varnished Cloth..... 174
- Varnished Paper..... 174
- Vectors..... 204
- Ventilation..... 213
- Visible Effect..... 4
- Volt..... 4, 7

Voltage of Edison Cell.....	160	— Moving Coil and Stationary Coil.....	96
Voltage Regulation of Generator	196	— Moving Coil and Stationary Permanent Magnet.....	88
Voltage of Lead Cell.....	158	— Plunger Types.....	94
Voltage Measurement.....	115	— Stationary Coil and Moving Iron.....	93
— With Voltmeter — Above its Range.....	116	— Types.....	88
— With Voltmeter — Below its Range.....	116	Voltmeters, Calibration (Experiment 2).....	277
— With Voltmeter — Within its Range.....	115	Ward-Leonard System.....	267
Voltmeter-Ammeter Method of Measuring Resistance.....	122	Watt.....	8
— Apparatus Required.....	122	Watt-hour Meter, Study of (Experiment 5).....	281
— Calculations Required.....	123	Watt-hour Meters.....	102, 137
— Method of Connection.....	123	— Commutator Type.....	103
— Where Used.....	122	— No-Commutator Type.....	106
Voltmeter-Ammeter Method of Measuring Resistance (Experiment 7).....	286	— Sangamo Meter.....	107
Voltmeter Method for Insulation Resistance.....	125	— Types.....	103
— Apparatus Required.....	125	— Use.....	102
— Insulation of "Dead" Lines.....	126	Wattmeter.....	136, 138
— Insulation of "Live" Lines.....	126	Wattmeter, Study of (Experiment 4).....	279
— Method of Connection.....	126	Wattmeters.....	99
— Theory.....	126	— Dynamometer Type.....	99
— Where Used.....	125	— Principles and Use.....	99
Voltmeter Method for Insulation Resistance (Experiment 9).....	289	Watt-second.....	19
Voltmeter Multipliers.....	87	Wave Winding.....	176
Voltmeters.....	87	Wave Wound Motor.....	243
— Care and Precautions.....	98	Wedge Rings.....	177
— Method of Connection.....	98	Wedges.....	175
Voltmeters and Ammeters.....	87	Weston Normal Cell.....	8
— D'Arsonval Type.....	88	What Determines Speed Finally Attained in Motor.....	242
— Difference Between.....	87	Wheatstone Bridge.....	117, 146
— Dynamometer Type.....	96	— Apparatus Required.....	117
— Electrostatic Type.....	97	— Method of Connection.....	118
— Hot-Wire Type.....	97	— Principle of Operation.....	118
— Induction Type.....	97	— Where Used.....	117
— Iron Bar Type.....	95	Wheatstone Bridge, Measurement of Resistance (Experiment 6).....	284
— Iron Vane.....	93		

Wheatstone Bridge Modifica- tions.....	120	Yoke.....	168
Windage.....	198	Zero Adjustment of Instruments.	98
Wooden Wedges.....	175	Zinc.....	141, 148
Work.....	8, 17	Zinc Chloride Solution.....	150

STANDARD BOOKS ON ELECTRICAL ENGINEERING

- ASHE, SYDNEY W.** *Electricity, Experimentally and Practically Applied.* A book for the beginner and for the practical man. *Second Edition, Revised.* 422 ill., $5\frac{1}{2} \times 7\frac{3}{4}$, 375 pp. **\$2.00**
- BEDELL, FREDERICK, and PIERCE, C. A.** *Direct and Alternating Current Manual.* With directions for testing and a discussion of the theory of electrical apparatus. *Second Edition, Greatly Enlarged.* Ill., 6×9 , 373 pp. **\$3.00**
- CARPMAEL, HERBERT.** *Electric Welding and Welding Appliances.* 84 ill., $7\frac{1}{2} \times 11$, 140 pp. **\$4.00**
- CISIN, H. G.** *Practical Electrical Engineering.* For Industrial and Evening Schools. Ill., $5\frac{1}{2} \times 7\frac{1}{2}$, 200 pp. *In Press*
- CHILD, CLEMENT D.** *Electric Arcs.* Experiments upon the arc between different electrodes in various environments and their explanation. 58 ill., 5×7 , 203 pages. **\$2.00**
- CLARKSON, RALPH P.** *Elementary Electrical Engineering.* A textbook of theory and practice, particularly adapted for the instruction of mechanical, civil, and chemical engineers and others desiring a short course. 143 ill., $5\frac{1}{2} \times 7\frac{3}{4}$, 202 pp. **\$2.00**
- CUSHING, Jr., H. C., and HARRISON, NEWTON.** *Central Station Management.* Compiled especially for the managers, superintendents and engineers of electric light and power central stations, and is in accordance with the latest accepted practice. $5\frac{1}{2} \times 7\frac{3}{4}$, 417 pp. **\$2.00**
- DEL MAR, WILLIAM A.** *Electric Power Conductors.* *Second Edition, Revised.* 69 ill., 6×9 , 330 pp. **\$2.00**
- DWIGHT, HERBERT B.** *Transmission Line Formulas for Electrical Engineers and Engineering Students.* 27 ill., 5×7 , 143 pp. **\$2.00**
- EDGCUMBE, KENELM.** *Industrial Electrical Measuring Instruments.* *Second Edition, Revised and Enlarged.* 260 ill., $5\frac{1}{2} \times 8\frac{1}{2}$, 430 pp. **\$5.00**
- FOSTER, HORATIO A.** *Electrical Engineers' Pocketbook.* A handbook of useful data for electricians and electrical engineers. With the collaboration of eminent specialists. *Seventh*

- Edition, Completely Revised.* 1128 ill., 718 tables, $4\frac{3}{4} \times 7$, flexible fabrikoid, 1636 pp. **\$5.00**
- GEAR, H. B., and WILLIAMS, P. F.** *Electric Central Station Distribution Systems.* Their design and construction. *Second Edition, Revised and Enlarged.* 187 ill., $5\frac{1}{2} \times 7\frac{1}{2}$, 455 pp. **\$3.50**
- GROTH, L. A.** *Welding and Cutting Metals by Aid of Gases or Electricity.* 124 ill., 6×9 , 280 pp. (Van Nostrand's Westminster Series.) **\$3.00**
- HAUSMANN, ERICH.** *Telegraph Engineering.* A manual for practicing telegraph engineers and engineering students. 192 ill., $5\frac{1}{2} \times 8\frac{1}{2}$, 416 pp. **\$3.00**
- HERING, CARL,¹ and GETMAN, FREDK. H.** *Standard Table of Electro-Chemical Equivalents and Their Derivatives.* With explanatory text on electro-chemical calculations, solutions of typical practical examples and introductory notes on electrochemistry. Ill., $4\frac{1}{8} \times 5\frac{5}{8}$, flexible fabrikoid, 140 pp. **\$2.00**
- JAMES, HENRY D.** *Controllers for Electric Motors.* A treatise on the modern industrial controller, together with typical applications to the industries. 259 ill., $5\frac{1}{2} \times 8\frac{1}{2}$, 360 pp. **\$3.00**
- JOHNSON, C. H., and EARLE, R. P.** *Practical Tests for the Electrical Laboratory.* A textbook for vocational schools. Ill., 6×9 . *In Press*
- MIESSNER, B. F.** *Radiodynamics.* The wireless control of torpedoes and other mechanisms. 112 ill., $5\frac{1}{2} \times 8\frac{1}{2}$, 211 pp. **\$2.00**
- MONTGOMERY, J. H.** *Electric Wiring Specifications.* $4 \times 6\frac{1}{2}$, 140 pp. **\$1.00**
- MORECROFT, J. H., and HEHRE, F. W.** *A Short Course in the Testing of Electrical Machinery.* *Fourth Edition, Revised and Enlarged.* 111 ill., 6×9 , 229 pp. **\$3.00**
- MORGAN, ALFRED P.** *Wireless Telegraph Construction for Amateurs.* *Third Edition, Revised and Enlarged.* 167 ill., 6 plates, $5\frac{1}{2} \times 7\frac{1}{2}$, 236 pp. **\$1.50**
- RASCH, E.** *Electric Arc Phenomena.* Translated by K. Tornberg. 52 ill., 5×7 , 187 pp. **\$2.00**
- RIDEAL, ERIC K.** *Industrial Electrometallurgy, Including Electrolytic and Electrothermal Processes.* Ill., $5\frac{1}{2} \times 8\frac{1}{2}$, 259 pp. (Industrial Chemistry Series.) **\$3.00**
- RIDEAL, E. K.** *Ozone.* 24 ill., $5\frac{1}{2} \times 8\frac{1}{2}$, 207 pp. **\$4.00**

- SHELDON, S., and HAUSMANN, E.** **Dynamo Electric Machinery.** Its construction, design and operation. In two volumes. Vol. I, **Direct Current Machines.** *Ninth Edition, Revised.* 218 ill., $5\frac{1}{2} \times 7\frac{3}{4}$, 337 pp.
Vol. II, **Alternating Current Machines.** *Tenth Edition, Completely Revised.* 236 ill., $5\frac{3}{4} \times 7\frac{3}{4}$, 364 pp. **\$2.50**
A new edition in one volume is in preparation.
- SHELDON, SAMUEL, and HAUSMANN, ERICH.** **Electric Traction and Transmission Engineering.** *Second Edition, Revised.* 127 ill., $5\frac{1}{2} \times 8$, 319 pp. **\$3.00**
- SLOANE, T. O'CONNOR.** **Elementary Calculations.** A manual of simple engineering mathematics, covering the whole field of direct current calculations, the basis of alternating current mathematics, networks and typical cases of circuits, with appendices on special subjects. Ill., $5\frac{1}{2} \times 8\frac{3}{4}$, 316 pp. **\$2.50**
- STONE, ELLERY W.** **Elements of Radiotelegraphy.** 125 ill., 33 plates, $5 \times 7\frac{1}{2}$, flexible fabrikoid, 274 pp. **\$2.50**
- SWOOPES Lessons in Practical Electricity.** An elementary textbook. *Sixteenth Edition*, rewritten, revised and enlarged by Harry N. Stillman and Erich Hausmann. 488 ill., $5\frac{1}{2} \times 7\frac{3}{4}$, 638 pp. **\$2.50**
- THIESS, J. B., and JOY, G. A.** **Toll Telephone Practice.** With an introduction by F. F. Fowle. 272 ill., 17 tables, $6\frac{3}{4} \times 9\frac{3}{4}$, 433 pp. **\$3.50**
- UNDERHILL, CHARLES R.** **Solenoids, Electromagnets and Electromagnetic Windings.** *Second Edition, Thoroughly Revised.* 224 ill., 5×8 , 363 pp. **\$3.00**
- VOSMAER, A.** **Ozone. Its Manufacture, Properties and Uses.** 75 ill., 6×9 , 210 pp. **\$2.50**
- WEBB, H. L. A.** **Practical Guide to the Testing of Insulated Wires and Cables.** *Sixth Edition.* 38 ill., $5\frac{1}{4} \times 7\frac{1}{2}$, 124 pp. **\$1.00**
- WILSON, JOHN F.** **Essentials of Electrical Engineering.** A textbook for colleges and technical schools. 300 ill., 6×9 , 350 pp. **\$3.00**

PUBLISHED BY

D. VAN NOSTRAND COMPANY

EIGHT WARREN STREET

NEW YORK

The **Literature of Engineering and the Industries**

¶ On our shelves is the most complete stock of engineering, scientific, technical and industrial books in the United States. A large number of these we publish and for an ever increasing number we are the sole agents.

¶ All inquiries are cheerfully and carefully answered and complete catalogs as well as special lists are sent free on request.



D. Van Nostrand Company
PUBLISHERS AND BOOKSELLERS
8 WARREN STREET NEW YORK



M



M



M



M



M



M



M

